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PREDICTION OF INSULATION DEGRADATION OF DISTRIBUTION POWER CABLES BASED ON CHEMICAL ANALYSIS AND ELECTRICAL MEASUREMENTS

Doctoral Dissertation

Petri Hyvönen

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Helsinki University of Technology
Faculty of Electronics, Communications and Automation
Department of Electrical Engineering

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Prediction of insulation degradation of distribution power cables based on chemical analysis and electrical measurements

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Supervisor	Professor Matti Lehtonen

This thesis deals with the prediction of medium voltage cable insulation condition. Different kinds of electrical measurements and chemical analyses are tested to find out the most representative combination. A large scale test program was carried out on field aged XLPE-insulated and oil-paper insulated cables. Cable samples were collected from different utility companies in Finland.

Degradation of XLPE-insulation will change insulation material properties and it should be possible to detect these changes with chemical analysis. These chemical changes can lower the voltage withstand level of XLPE-cables. Degradation of paper insulation will decrease the mechanical properties of the paper. Increased moisture content will affect the electrical performance of the oilpaper insulation and will also speed up degradation processes. Methods such as dielectric response measurement and FTIR-analysis were used to determine the degree of degradation.

It was found that XLPE-cables used in friendly environments are still in good condition after thirty years of service. Cables can be ranked clearly into different condition classes, but overall the XLPE-cables were in good condition. The FTIR-analysis results had good correlation to the voltage withstand levels of the cable samples.

The field aged oilpaper insulated cables were also in good condition, even after more than fifty years of service life. Insulations were dry and degree of polymerisation (DP-value), related to mechanical strength, were high. FTIR-analysis results showed good correlation to the moisture content in the insulation. Since increased moisture content and high temperature will increase degradation rate significantly, FTIR-analysis can be used to estimate oilpaper insulation condition.

Based on the research project results, FTIR-analysis can be used to estimate cable insulation condition. Results of FTIR-analysis can be linked to the voltage withstands levels of XLPE-cables and the moisture content of oilpaper cables. FTIR-analysis results can be converted to the condition classes of XLPE and oilpaper insulated cables.

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Tässä väitöskirjassa on tutkittu mahdollisuuksia arvioida ja ennustaa keskijännitekaapeleiden kuntoa perustuen erilaisiin sähköisiin mittauksiin ja kemiallisiin analyyseihin. Työssä tutkittiin erilaisten mittaus- ja analyysimenetelmien soveltuvuutta kunnon määrittämiseen. Tutkimuksen aikana toteutettiin laaja testausohjelma käytöstä poistetuille keskijännitekaapelille, jotka oli kerätty eri verkkoyhtiöiltä Suomesta.

PEX-eristyksen rappeutuminen muuttaa eristysmateriaalin ominaisuuksia ja nämä muutokset on mahdollista havaita kemiallisilla analyyseillä. Kemialliset muutokset voivat alentaa PEX-eristyksen jännitekestoisuutta. Paperieristyksen rappeutuminen heikentää paperin mekaanista lujuutta. Kohonnut kosteuspitoisuus heikentää öljypaperieristyksen jännitekestoisuutta ja samalla kiihdyttää rappeutumista. Diagnostisia menetelmiä, kuten sähkövasteen mittausta ja FTIR-analyysiä käytettiin eristyksen rappeutumisen havaitsemiseen.

Tulosten perusteella hyvissä ympäristöolosuhteissa 30 vuotta käytetyt PEX-eristeiset kaapelit olivat vielä hyvässä kunnossa. Kaapelit voitiin luokitella kuuluviksi eri kuntoluokkiin, mutta yleisesti kaikki testatut kaapelit olivat vielä hyvässä kunnossa. FTIR-analyysin tulosten ja kaapeleiden jännitekestoisuuden välille oli löydettävissä korrelaatio.

Yli 50 vuotta käytössä olleet öljypaperieristeiset kaapelitkin olivat vielä hyvässä kunnossa. Paperieristykset olivat kuivia ja mekaanista lujuutta kuvaavat DP-luvut olivat korkeita. FTIR-analyysin tulosten ja eristyksen kosteuden välillä oli hyvä korrelaatio. Kohonnut kosteuspitoisuus yhdessä korkean käyttölämpötilan kanssa kiihdyttää ränsistymistä merkittävästi. FTIR-analyysin tulosta voidaan käyttää arvioitaessa öljypaperieristyksen kuntoa.

Tulosten perusteella FTIR-analyysiä voidaan hyödyntää kaapeleiden kuntoa arvioitaessa. FTIR-analyysin tulosten ja PEX-eristeisten kaapeleiden jännitekestoisuuden sekä FTIR-analyysin tulosten ja öljypaperieristyksen kosteuden välillä on selvä korrelaatio. Kaapelit voidaan luokitella eri kuntoluokkiin FTIR-analyysin tulosten avulla.

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Preface

This work was carried out at the Power Systems and High Voltage Laboratory of the Helsinki University of Technology (TKK). Work in the field of cable diagnostics was started at the beginning of 2000. Since then, three projects dealing with diagnostics issues in medium voltage cable systems have been carried out.

The first project called KaVika focused on a literature survey on the field of cable diagnostics. The following project KaDiat focused more on collecting and analysing data from real cable systems in use. The measurement of dielectric response and partial discharges were the main diagnostics methods applied. The latest project KaLifi concentrated more deeply on the analysis and estimation of the remaining lifetime of different cable insulation types used in Finland.

A certain part of this work is based on findings from previous projects. The experimental part of the work is mainly based on results and findings from the KaLifi-project. The KaLifi-project as well as the other previous projects have been carried out with close co-operation between TKK and Finnish industry, utility companies and service providers. It has been possible to collect a large amount of on-site as well as laboratory experience on a wide range of cable types and ages due to such good co-operation.

Acknowledgements

I would like to thank my supervisor professor Matti Lehtonen, the head of the power systems and high voltage laboratory at TKK, for his guidance and help in the supervision of this work. During the previous cable projects the former head of the high voltage institute, Professor Martti Aro, also gave a lot of valuable information and instruction, for which I am most grateful.

Organizations participating in the KaLifi-project and the organisations which participated in our previous projects have made it possible to perform this study. Thanks to all these organisations for funding, steering and commenting on the projects. The R&D manager Mr. Tuomo Martinmäki from Tervakoski Films Group provided valuable test reports from artificial ageing tests on different paper grades in the 1960s. The TKK Forest product chemistry laboratory and especially Dr. A-S Jääskeläinen helped to carry out the FTIR-analysis and paper analysis work. I am grateful to Mr. John Millar for the language check and corrections.

All present and former personnel in the Power Systems and High Voltage Laboratory and the previous High Voltage Institute have helped me a lot in this project. That is why I would like to give them all the big thanks.

Most of all I would like to thank my wife Annikki and our children Roope and Meri for their support and encouragement doing this work.

Espoo Finland 2008 *Petri Hyvönen*

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List of abbreviations

AC	Alternating current
AHXCMK	XLPE-insulated medium voltage cable with copper wire screen
AHXAMK-W	XLPE-insulated medium voltage cable with aluminium laminate screen
AHXDMK	XLPE-insulated medium voltage cable with corrugated copper foil screen
APAKM	Oil-paper insulated medium voltage cable, belt insulated
APYAKMM	Core type oil-paper insulated medium voltage cable, core type insulation
APYAKMT	Core type oil-paper insulated medium voltage cable, core type insulation
ASTM	International standards organisation
AXKJ	XLPE-insulated medium voltage cable with copper wire screen
BD	Breakdown test
CED	Cupri-ethylenediamine solution
CF	Conductivity factor
DC	Direct current
DP	Degree of polymerisation
FDS	Frequency domain spectroscopy
FTIR	Fourier transformed infra red
HDPE	High density polyethylene
HXCMK	XLPE-insulated medium voltage cable, with copper wire screen
IEC	International electrotechnical committee
NT	Needle test
PAS	Photo acoustic spectrometry
PDC	Polarisation and depolarisation current method
PI	Polarisation index
PLKVJ	Oil-paper insulated medium voltage cable, belt insulated
PNLKVg	Oil-paper insulated medium voltage cable, belt insulated
ppm	Parts per million
SCAN-CM	Scandinavian Pulp, Paper & Board Testing Committee
TKK	Helsinki University of Technology
UV	Ultra violet
XLPE	Cross linked polyethylene

List of symbols

ϕ	Activation energy
φ	Angle
ω	Angular frequency
σ	Conductivity
ψ	Nonlinearity factor
η	Viscosity
$\varepsilon^*(\omega)$	Complex permittivity
ε'	Imaginary part of complex permittivity
ε''	Real part of complex permittivity
σ_{30s}, σ_{60s}	Conductivity at 30 and 60 seconds
ε_o	Permittivity
A	Constant
a, b	Constants
δ	Angle
C^*	Complex capacitance
C_o	Geometrical capacitance
DP_o	Degree of polymerisation at the beginning
DP_t	Degree of polymerisation at the end
d	Thickness of insulation
E_{max}	Maximum applied electric field
H_1, H_0	Hypothesis of statistical test
I_C	Capacitive current through insulation
I_{Da}	Depolarisation current caused by lowest charging voltage
I_{dp}	Depolarisation current
I_M	Total current through insulation
I_p	Polarisation current
I_{p60}, I_{p600}	Polarisation current at 60 and 600 seconds
I_R	Resistive current through insulation
k	Boltzman’s constants
L	Time to reach end of life
mc	Moisture content
N	Number of samples
R	Molar gas constant
r	Radius

R_{60}, R_{600}	Resistance at 60 and 600 seconds
T, T_a, T_o, T_s	Absolute temperature
t_a, t_o, t_s	Time
tanδ	dissipation factor, loss factor
$tan\delta_{min}$	Minimum of loss factor
t_{ch}	Charging time
t_{oc}	Open circuit time
t_{sc}	Short circuit time
U	Applied voltage
U_a	Lowers charging voltage
U_A	Sinusoidal excitation
U_{ch}	Charging voltage
U_o	Nominal phase to ground voltage of cable
U_{rvm}	Return voltage
Z(ω)	Impedance

1 Introduction

1.1 Background

Electric power systems include a large number of expensive and important power cable systems of different age manufactured and installed over many decades. The oldest oil-paper insulated cables still in use were installed in the 1940s. Installation of XLPE-cables started in the middle of the 1970s. Some of the oil-paper insulated cables are rather old and the first XLPE cables are old enough to show possible degradation results.

For reliability reasons, preventative measures need to be taken on certain components in the power system. Quality requirements are increasing and outages in electric power distribution are expensive. Condition based maintenance is becoming more common for economic reasons. Repair and replacement of important cable systems are expensive and correct timing in these activities can give large savings in costs.

The insulation systems of high-voltage power cables and their accessories are subject to different kinds of stresses during their service life and thus suffer degradation and deterioration. These can lead to a reduction of life which in turn can lower the reliability of electrical power systems. Therefore, a lot of research effort, activities and publications are directed towards a better understanding of degradation phenomena, the finding of tools for insulation diagnosis and the establishment of remaining life estimation techniques. In order to check the quality and dependability of a cable system, it is important to perform diagnostic tests before putting the cable system into operation and after a defined period of operation. On-site insulation diagnosis to determine the degradation state of high voltage equipment is of great interest within the power and grid companies and utilities.

It is impossible to carry out diagnostics measurements on all cable systems in use. It is even harder to carry out full laboratory scale testing of every cable system in use. Cable insulation must be stripped and cut during the repair of a cable fault. This is a natural point to collect cable insulation samples for further analysis. Analysis results should give more information about the actual condition of the cable insulation system.

1.2 Objective of the thesis

This work is divided into two parts, the first related to polymer insulated cables and the second to oil-paper insulated cables. The aim of this work is to test and answer the following hypothesis.

- Degradation of XLPE cables can be detected using chemical analysis, electrical tests and measurements and these results can be linked together to produce cable condition classes.
- Oil paper insulation degradation can be predicted using paper analysis and electrical measurements.

The results of this work are based on experimental tests on field aged XLPE and oil paper insulated cables and further analysis of previously performed tests. The aim is to find practical methods to evaluate chemical analysis results. The overall analysis of chemical analysis results would require a deep knowledge of chemistry and in this work this is not the objective. The

major task in this thesis is to discover methods that can be easily adapted for every day use in the field of cable condition monitoring.

1.3 The author's contribution

The main contribution of this study is the establishment of condition classification tools to evaluate XLPE-insulated and oil-paper insulated medium voltage power cables. On XLPE-insulated cables this condition classification combines FTIR-analysis results and voltage withstand levels. On oilpaper insulated cables FTIR-analysis results are combined with the expected operation temperature and expected lifetime of paper insulation.

In this thesis, different kinds of electrical measurements and chemical analysis have been performed on different types of field aged cables. Large numbers of field aged XPLE insulated cables and oil-paper insulated cables were taken out of service and transported to the high voltage laboratory for diagnostics measurements and analysis. The applicability of the various diagnostics methods, such as dielectric response measurement, needle test, breakdown test, FTIR-analysis and paper analysis, were tested on field aged cables.

Results of previous artificial ageing tests on paper are presented and analysed from the 1960s. The results of artificial ageing tests and the experimental part of this study are combined with condition classification tools for oil-paper insulated cables.

1.4 Organization of the thesis

Organization of the thesis is as follows:

- Chapter 2 introduces XLPE insulation, the XLPE material itself, the manufacturing of cable insulation and the different degradation mechanisms that affect insulation.
- Chapter 3 introduces oil-paper insulation, materials, cable insulation manufacturing and degradation mechanisms that have an effect on oil-paper insulation.
- Chapter 4 gives an overview of the different diagnostics measurements and methods used in this thesis. The background of the methods as well as the basic evaluation of measurement results are presented.
- Chapter 5 deals with the experimental investigation on XLPE-insulated cables. Results from the laboratory measurement and analysis of XLPE-insulated field aged medium voltage cables are shown. Combined test results are presented with a discussion.
- Chapter 6 deals with the experimental part on oil-paper insulated cables. Results from laboratory measurements and an analysis of oil-paper insulated field aged medium voltage cables are shown. Combined test results are followed by a discussion.
- Chapter 7 summarizes the results and findings of the work and gives ideas for future work.

2 Crosslinked polyethylene insulation (XLPE)

Since the end of the 1960s, crosslinked polyethylene (XLPE) insulated power cables have increasingly come into use. All new installations and repairing of old cable systems are performed using XLPE-cables.

The basic material of XLPE is low density polyethylene (LDPE). XLPE is usually produced by the activation chemical agent, dicumyl peroxide. Insulation is extruded over the conductor using triple extrusion. During the triple extrusion process, polyethylene mixed with dicumyl peroxide is pressed onto the conductor forming the inner conductor screen, and the main insulation and outer semi conductive layers are extruded at the same time. The temperature during the extrusion is around 130 ºC. After extrusion the insulated core is passed through a vulcanisation tube filled with pressurised and heated nitrogen gas. The heat and pressure decompose the peroxide into reactive primary radicals which affect the crosslinking. The crosslinking process causes polyethylene to change from a thermoplastic to thermosetting material with a marked improvement in both the physical and electrical properties.

After the curing the cable is cooled down. This period can cause residual mechanical stresses inside the cable insulation, which may not be uniformly distributed in the cable insulation bulk material. Residual internal mechanical stresses from manufacturing have a significant effect on the breakdown strength of cable insulation [1]. The effect of internal mechanical stress can be reduced by heat treatment. Intermediate storing of the cable before jacketing will also reduce mechanical stresses.

During the curing process crosslinking byproducts are formed. Water is formed while crosslinking polyethylene and forming XLPE. At the same time acetophenone and cumyl alcohol are formed in the quantity of 1 weight percent of the fresh vulcanised insulation. Up to 99,5 % of the peroxide will be consumed during the curing process. After degassing the insulation, the peroxide residual will be less than 4000 ppm and the water byproduct should be less than 150 ppm [2].

The long term performance of XLPE insulation can be improved using additives during the manufacturing. Additives can improve the water tree retardant capabilities. Antioxidants are added to the cable insulation to capture highly reactive and harmful free radicals.

2.1 Crosslinked polyethylene degradation

The degradation processes of XLPE insulation can be categorized into two main groups as either extrinsic, i.e., those due to voids, contaminants, physical imperfections or poorly dispersed components, or intrinsic, i.e., those due to physical or chemical changes or trapped charges [3]. An intrinsic degradation process may affect a large volume of insulation, for example thermal degradation of the insulation material. Extrinsic degradation usually results in localised changes in otherwise uniform insulation material.

Physical, chemical and electrical degradation are the major deterioration mechanisms affecting polymeric insulation. Polymers will not achieve their final crystal structure right after manufacturing. Final curing of the insulation structure will happen over several years, because

curing is a slow process whereby micro cavities and locally denser areas can be formed inside the insulation. Uneven insulation structure will increase the effect of electrical degradation and the risk of electrical breakdown. Polymeric insulation is sensitive even to small partial discharges [6]. The molecular structure of polyethylene is modified by mechanical degradation. Mechanical stress is known for generating bonds deformation, free radicals and rupture, and also carbonyl croups in polyethylene [41].

2.1.1 Chemical degradation

Chemical degradation will cause changes in the mechanical properties of polymeric insulation. The result of chemical degradation can be to break up the long polymeric chains, a process known as depolymerisation. Some new cross-linking bridges can be also formed. Polymeric insulation will be more brittle if these mechanisms are in play. Chemically reactive free radicals are part of the reaction. These free radicals are formed during the oxidation of the insulation. The formation rate of free radicals depends on temperature, the amount of oxygen and the presence of radiation. Note that ready made cable insulation does not contain a free oxygen source. Oxidation refers to all changes in the oxidation state of the material. Partial discharges inside the insulation will form ionising radiation, causing the formation of free radicals. As consequence of partial discharges, some harmful gases and acids are formed. Sunlight contains UV-radiation, which is also harmful for polymeric insulation.

2.1.2 Formation of free radicals

Free radical formation is the initial step in polymer degradation. The sharing of a pair of valence electrons between two atoms forms a covalent bond. In heterolytic dissociation both bonding electrons are retained by one of the atoms and ionic species are formed. In a less typical process each atom involved receives one electron from the original shared pair. An atom that contains an unpaired electron is called a free radical. Most free radicals are unstable and very reactive, because free radicals contain an atom with an incomplete octet [2].

Ionisation is typically caused by accelerated electrons in the material. An electron does not necessarily deliver all of its energy to the molecule it interacts with. Since organic molecules almost without exception contain electron pairs in filled orbitals, the ionisation of a molecule by removing an electron leaves behind an electron which is unpaired. The product is a cation radical.

In the presence of oxygen, initially formed free radicals will react with oxygen forming peroxy complexes, and further, peroxy radicals. The peroxy has self catalytic effect on the degradation mechanism, accelerating the reaction through lower activation energy. Degradation products are oxy compounds such as aldehydes and ketones [2].

The primary antioxidants are free radical scavengers that terminate free radicals, forming a stable compound with them. Phenols, bisphenols, polyphenols and thiobisphenols are the primary antioxidants in greatest use [2].

2.1.3 Polymer radical degradation mechanism

The polymer radicals are formed through various mechanisms in discharges, oxidation and autocatalytic thermal scission. The effect of UV and gamma radiation and ozone causing ion

formation can be neglected during the normal operation of cables. Discharge activity depends on electric field stress and the frequency, and the number and distribution of possible discharge locations.

Polymer degradation caused by the polymer radicals can be grouped into three categories: addition to the polymer chain by branching or net formation, chain scission and oxidation by absorbed oxygen. Branching will make the material harder while scission and oxidation cause loss in molecular weight and increase brittleness. Oxidation also increases polarity and the loss factor of insulation material. Individual reactions are complicated and almost always impossible to measure directly.

2.1.4 Thermal degradation

During normal operation cable XLPE insulation temperatures should be below 90 ºC while during fault conditions cables can be used at temperatures of up to 120 ºC. At temperatures between 150 to 225 ºC, free radicals may attach to the backbone of the other polymer chains causing crosslinking. Crosslinking will decrease mechanical strength, density and crystallinity. At temperatures higher than 225 ºC, the formation of trans-vinyl groups is observed. Formation of trans-vinyl groups indicates radical rearrangements. At very high temperatures above 350 ºC polyethylene degradation takes place through de-polymerisation and incomplete thermal cracking forming coke.

2.1.5 Electrical degradation

The most dangerous defects in polymeric insulation are caused by electrical degradation. Partial discharges, electrical trees and water trees are the most important mechanisms. Electrical degradation will affect the insulation locally and randomly. Electrical degradation does not affect whole cable length, as thermal degradation does. The defect leading to final breakdown will usually be a local phenomenon. Low electric field intensity and long development time are common for electrical degradation mechanisms in medium voltage cables.

2.1.6 Water treeing

The majority of XLPE insulated cables installed in the ground are exposed to moisture and as a result are susceptible to degradation due to water trees. Water trees are generally found to initiate and grow in XLPE insulation exposed to an alternating electric field and humidity. Impurities inside the insulation material will increase the risk of water tree initiation. Polyolefins are capable of taking 2000 – 5000 ppm of water depending especially on the crystalline, which in the case of polyethylene is directly related to the material's specific density [2]. Water can penetrate the insulation from the outside environment of the cable if water blocking barriers are not used. Water can also enter cable insulation from termination or joint faults.

The formation of water trees starts at microscopic inhomogeneities in the insulation. Moisture inside the insulation will start to propagate in the direction of the electric field in a bush or tree form. Two types of water tree exist, bow-tie and vented. Bow tie water trees initiate from impurities and voids within the bulk insulation and tend to grow in two directions. Bow tie trees reach a limiting length of some tens of μm, and do not have a significant effect on degradation at the low electric field stresses used in distribution cables [4]. Residual moisture from crosslinking

may also produce small bow tie water trees, but these water trees are not considered to be harmful. Vented water trees are initiated at the interface between the semiconductive screens and insulation and grow in the same direction as the applied electric field. Vented water trees normally need a longer initiation time than bow tie trees. Bow tie water trees saturate after a certain length, but vented water trees continuously grow and may eventually penetrate the entire insulation thickness. Thus vented water trees are considered to cause more severe degradation than bow tie water trees [5]. Water trees cause local stress enhancement that may be the initiation phase for an electrical tree. Alternatively, significant oxidation may occur in trees at high temperatures, leading to increased absorption, higher conductivity, and eventually thermal runaway [4]. Figure 2.1 shows two examples of vented type water trees.

The difference between a water and an electrical tree is that water trees do not necessarily form a permanent and visible canal through the insulation. When electric field and moisture are removed, water trees can ostensibly disappear. Total breakdown of the insulation can happen when a branch of a water tree bridges the electrodes. In some cases a cable can handle normal operating voltage even when a water tree bridges the electrodes. Formation of the water trees will take years. Growth of the water trees depends on the presence of water, the intensity and frequency of the electric field, the insulation material, temperature and mechanical stresses.

Water trees are formed at lower electric field strengths than electrical trees. Obviously cables installed in moist environments should be protected against moisture penetration to the insulation.

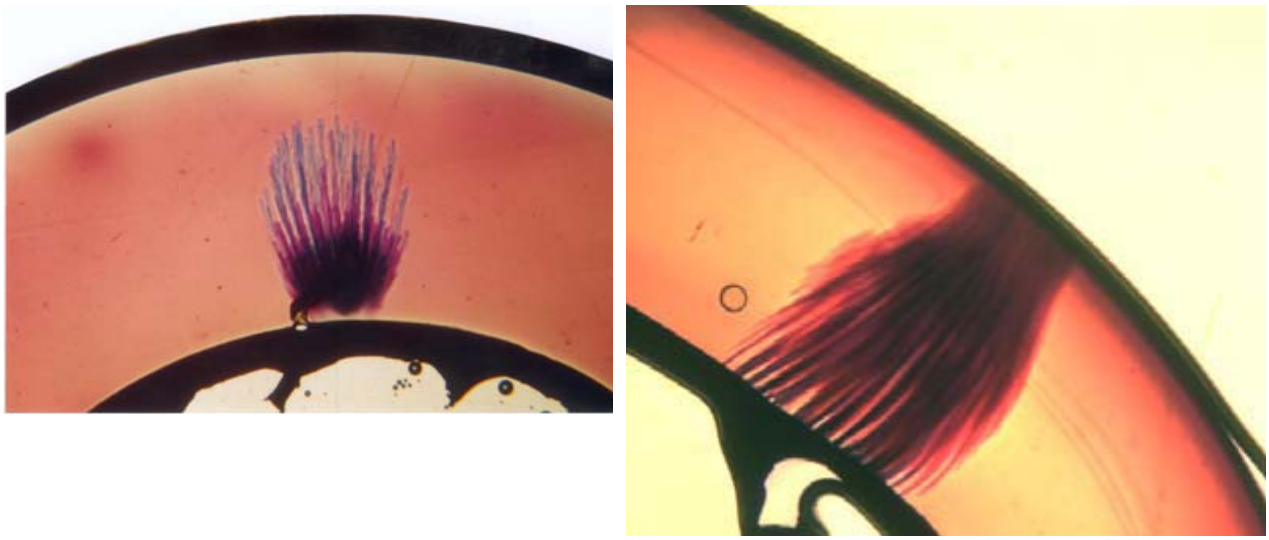

Figure 2.1 On the left hand side an example of a vented water tree growing from the conductor screen and on the right hand side an example of a vented water tree bridging the whole insulation [58].

2.1.7 Electrical treeing

An electrical tree is a network of fine conductive channels that propagates relatively quickly through the insulation to cause failure. Electrical trees can initiate from the eroded surface of the void or a water tree or initiation can take place in the micro cavities of the polymer if the electric

field enhancement is large enough. There are two phases of electrical treeing. During the initiation phase the charge motion (0,1 – 0,2 pC) of each half cycle of the applied voltage gradually degrades the polymer leading to the formation of a small void. The charge injection and electroluminescence caused by the electric field enhancement in the insulation plays a certain role during the initiation phase of an electrical tree. When subjected to AC voltage stress polyethylene emits light in the visible and UV ranges above a certain threshold voltage, due to the charges of positive and negative polarities injected into the polymer. The UV light causes photo degradation due to the photochemical reactions, creates free radicals and breaks bonds leading to the formation of a microcavity and subsequently an electrical tree [60].

During the growing phase a tree-like network of branches is formed from the expanded void due to the partial discharges within the branches. Discharges of 5 pC are enough to cause thermal runaway and extensive local thermal degradation of the polymer [2]. The tree growth rate depends on the applied electrical stress, the temperature, and the environmental and mechanical stresses.

During the manufacture or installation of a cable and its accessories, small cavities or gas bubbles can form inside the insulation or in the surface between insulation layers. When the electric field intensity inside a cavity or bubble is high enough, partial breakdown will occur. Positive charged ions and electrons formed by the partial breakdown will collide on the surface of the insulation and degradation of the insulation material will start.

The roughness of the cavity surface or impurities inside the insulation can lead to a concentration of partial discharges in one place. The concentration of partial discharges will lead to a concentrated region of degradation in the insulation material. A conducting canal in the form of a bush or tree starts to develop through the insulation. This formation is known as an electrical tree. Total breakdown of the insulation can happen when the branch of an electrical tree bridges the electrodes. Breakdown can also occur before the electrical tree bridges the electrodes.

3 Oil-paper (mass) insulation of medium voltage cables

Oil-paper insulation is one of the oldest insulation structures used in power cables. The oldest oil-paper insulated medium voltage cables still in use in Finland were installed in the 1940s. Electrical grade paper is mostly made from wood pulp produced by the kraft chemical process. The starting point of paper is wood. Cellulose is a polymer of glucose units linked to one another in a special manner, as shown in Figure 3.1. Cellulose may be present simply as $[C_5H_{10}O_5]_n$, ignoring the extra atoms on the end groups, where n is degree of polymerisation (DP). A typical DP value for kraft paper is around 1100 to 1500, meaning that a single cellulose fibre has from 1100 to 1500 glucose molecules. In the chemical process lignin is selectively dissolved and removed, although about 5 % remains. Kraft paper consists of cellulose, hemicelluloses and residual lignin. For electrical grade pulp bleaching is not performed, but careful washing is required to remove ionic particles. The pulp sheets are fed into a large vat where the fibres are separated and mixed to the right consistency. Water is sucked off by suction pumps. For paper making a Fourdrinier press is commonly used [26]. The long term degradation performance of insulation paper can be improved by thermal upgrading. During thermal upgrading substitutes such as dicyandiamide ether are linked to the OH-groups in the cellulose. Also, organic bases such as melamine or dicyandiamide can be linked to neutralize the acidic compound produced by oil and paper degradation.

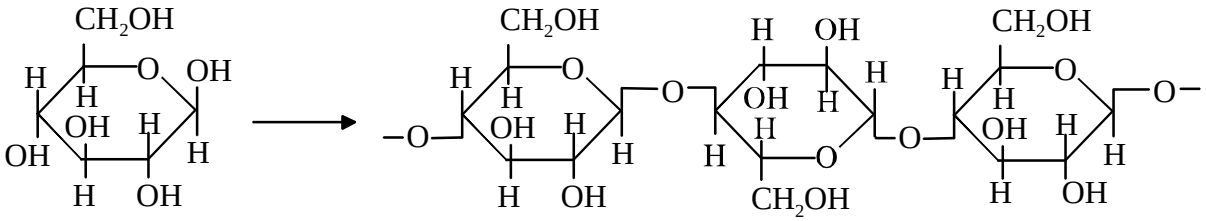

Figure 3.1 Glucose molecule and cellulose polymer.

10 – 20 mm wide paper strips are wrapped around the cable conductor. There will be a small gap between parallel paper strips. The next layer is wrapped on the top of the previous one, so as to avoid the formation of closed channels between the layers. The thickness of the paper strips varies from 50 to 200 μm. The thinnest are used near the conductor. Cables are vacuum treated after the wrapping of the paper strips. Moisture and air is removed during heat treatment. After heat treatment, the cable insulation is impregnated with mineral or synthetic oil. Oil will impregnate the paper and fill the gaps between paper layers. Medium voltage cables are impregnated with oil that does not flow easily at ambient temperature. The viscosity of oil used in medium voltage cables is higher than that of the oil used in transformers. Medium voltage cables are often referred to as mass impregnated cables or mass cables.

Oil-paper insulation is unhomogeneous due to its structure. The electric field in oil is about twice the strength of the electric field in paper. The distribution of the electric field is determined by the relative permittivity of oil and paper. The paper makes possible the formation of thin oil layers. The electric field strength in these thin oil layers is high. Paper layers will also block the

movement of impurities from layer to layer. The paper, metallic sheath and armouring make up the mechanical rigidity of a cable.

3.1 Oil-paper insulation degradation

The properties of oil and paper will change during their life time. Some of the changes are related to normal ageing and some are related to external stresses. External stresses can speed up the degradation of insulation material dramatically. Cables are subjected to different kinds of mechanical, thermal and electrical stresses during their operation. The total stress of a cable is the sum of different stresses. Very rarely does only one type of stress act alone. The total effect of all the different types of stresses is almost impossible to model.

Oil is an organic material and it will change due to the presence of oxygen. This change is a chain reaction that starts when the hydrocarbon molecules of oil are oxidised to form hydrogen peroxide. Hydrogen peroxide decomposes easily forming free radicals. Free radicals are highly reactive and they easily oxidise forming more new free radicals. Precipitates, conductive impurities, water and acids are formed in oil due to degradation. Metallic sheaths are used in oil-paper cables. A metallic sheath is an effective moisture blocker and in normal conditions the degradation of oil is a slow process.

Three different degradation mechanisms, hydrolytic degradation, oxidation and thermal degradation, take place when insulation paper is in use. In the case of cables, hydrolytic degradation is the main degradation mechanism. Cable insulation is quite well protected against oxygen and high temperatures. In the case of transformers, oxidation and thermal degradation mechanisms also play an important role. Water and acids in oil-paper insulation degrade paper insulation.

Hydrolytic degradation is caused by water and acids cleaving the glycosidic bond between glucose monomers yielding the formation of free glucose. The result is a reduction in the degree of polymerisation and weakening of paper mechanical properties. Oxidation takes place when oxygen attacks the carbon atoms in the cellulose molecule. Aldehydes, water, acids and carbon monoxide are produced. Bonds between cellulose are weakened, leading to a lower degree of polymerisation. Water released by this mechanism can contribute to the hydrolysis [47].

Thermal degradation or pyrolysis of cellulose in the absence of oxidizing agents and moisture will lead to breaking of the clycosidic bond and opening of the glucose rings. Free glucose molecules, moisture, carbon oxides and acids are formed. Moisture is the most powerful degrading agent of paper insulation [48]. Moisture will be formed or consumed depending on the degradation process, e.g. the formation of acetic acid will consume moisture. Pyrolysis can take place without access to oxygen or moisture. During normal operation when the temperature is below 140 °C, pyrolysis processes are considered to be of little relevance [59]. Figure 3.2 shows different degradation processes and their main products [48].

Degradation of paper mainly affects its mechanical properties; its electrical properties are only slightly changed [27]. During degradation the degree of polymerisation of the insulating paper is decreased. The degree of polymerisation of new paper is around 1100 to 1500 while a value less than 500 indicates significant thermal degradation [28]. Weakening of mechanical properties can lead to cable failure during short circuits.

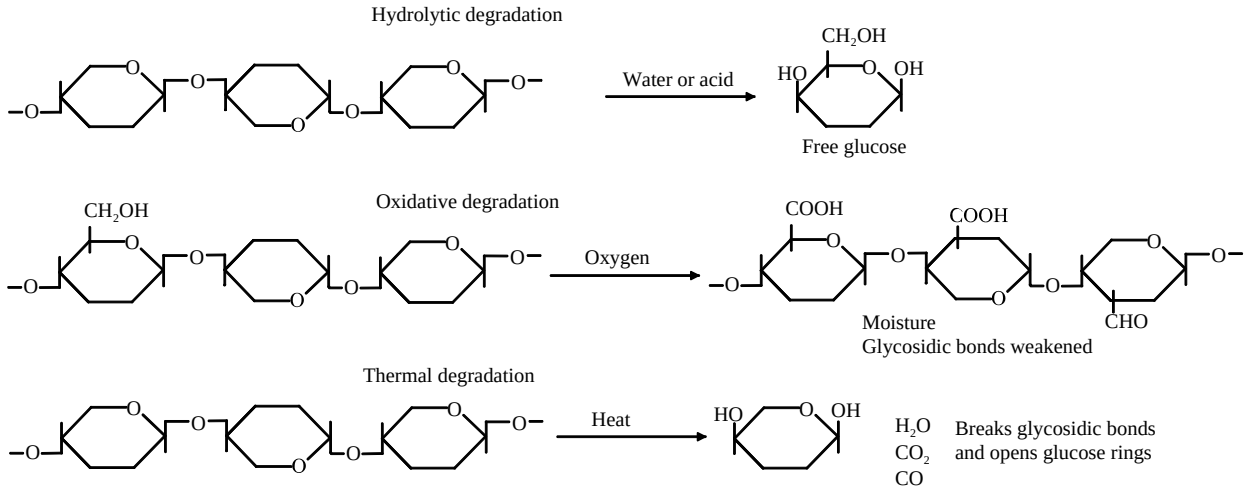

Figure 3.2 Degradation of cellulose [48].

The areas between the paper strips in cable insulation are oil filled. Different kinds of gases can be produced during the degradation of cables. Gases such as carbon monoxide, carbon dioxide and smaller amounts of hydrogen, methane, ethane and ethylene are produced. These gases can displace the oil and fill the areas between paper strips forming gas filled cavities. The electric field strength inside a gas cavity is higher than in the surrounding insulation. When the withstand level of the cavity is exceeded partial discharge will occur. Partial discharge can produce new gas filled cavities and conductive particles such as carbon. The withstand level of oil is reduced because carbon particles tend to dissolve in oil. Oil-paper insulation is partly self healing with respect to partial discharge phenomena. Partial discharges and gas filled cavities can disappear because the oil can move and replace the gas in cavities. Mechanical stresses can also promote the inception of partial discharges. Partial discharge related degradation and diagnostics is covered in more detail in reference [27].

4 Diagnostics methods

The aim of diagnostics methods is to detect the actual condition of insulation or detect changes in insulation condition or structure. Diagnostics methods or tests can be divided into two main categories: destructive and non-destructive methods. Diagnostics methods can be categorised in terms of whether they can be used on site or not.

Normally all diagnostics methods used on real insulation systems on site should be non-destructive. Condition indicators should be measured before any breakdown of the insulation system occurs. The diagnostics methods used in this study are listed in Table 4.1.

Table 4.1 Diagnostics methods.

Diagnostics method	Insulation	Indicator	Description
Dielectric response in time domain (PDC)	XLPE Oil-paper	Water trees, moisture	Off-line, on-site, non destructive
Dielectric response in frequency domain (FDS)	Oil-paper	Moisture	Off-line, on-site, non destructive
Frequency domain infra red spectroscopy (FTIR)	XLPE Oil-paper	Moisture, chemical changes	Off-line, off-site, destructive
Needle testing	XLPE	Voltage withstand	Off-line, off-site, destructive
Breakdown testing	XLPE Oil-paper	Voltage withstand	Off-line, off-site, destructive
Degree of polymerisation	Oil-paper	Degree of polymerisation	Off-line, off-site, destructive
Moisture content	Oil-paper	Moisture content	Off-line, off-site, destructive
Tensile strength and elongation	XLPE	Material strength and stiffness	Off-line, off-site, destructive

4.1 Dielectric response measurement

Diagnostic tests aim at detecting any reduction of the electrical strength due to degradation processes. Thermal and mechanical degradation are two major deterioration mechanisms affecting oil-paper insulation. Physical, chemical and electrical degradation are the major deterioration mechanisms affecting polymeric insulation.

These degradation mechanisms cause structural changes, and generally increase the polarisation intensity and conduction in the cable insulation. A change in structure usually increases the dielectric losses. For investigation of the changes in structure many tests are used. Based on electrical diagnostic parameters measured or derived from the measured data these tests give information on the stages of destruction as well as the causes of stress or degradation in the cable insulation. Over the past years several non-destructive diagnostics methods have been developed and taken into use. Dielectric response measurement is based on the fact that

water treeing and increased moisture content cause measurable changes in the dielectric properties of insulation material.

Dielectric response can be measured in different ways. The relevant parameters from dielectric response tests become evident when considering and comparing the dielectric responses of different insulations or the dielectric responses of the same insulation after certain periods in service. Preferably, certain parameters should be kept constant [8]. A detailed theoretical background of dielectric response measurement is presented in reference [12].

4.1.1 Time domain dielectric response measurement

In the time domain the dielectric response appears as a depolarisation current, return voltage (sometimes called residual, recovery and build-up voltage) and polarisation current. The measurements in the time domain are based on the application of a high DC voltage across the insulation for a certain time. Figure 4.1 shows a schematic presentation of dielectric response measurements in the time domain [9]. During the charging time t_{ch}, the polarisation current I_p and the depolarisation current I_{dp} can be measured during the short circuit period t_{sc}. The return voltage U_{rvm} can be measured if the test object is open circuited after the short circuit period. Practical measurements of dielectric response in the time domain are based on the measurement of either a single existing component or various combinations of components

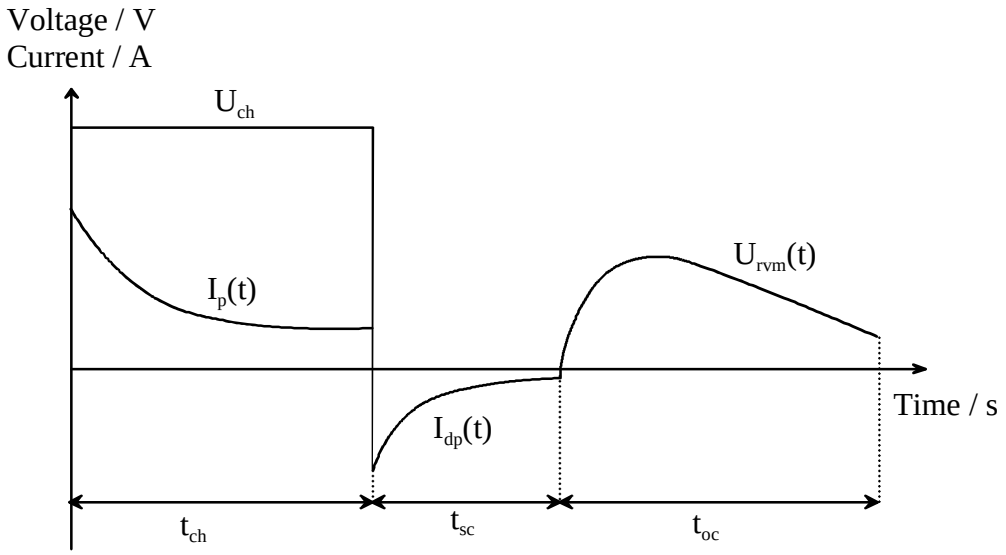

Figure 4.1 Representation of measurement of dielectric response in time domain. U_{ch} = charge voltage, $I_p(t)$ = polarisation current, $I_{dp}(t)$ = depolarisation current, $U_{rvm}(t)$ = return voltage, t_{ch} = charging period, t_{sc} = shot circuit time, t_{oc} = open circuit time.

In this work measurement of dielectric response in the time domain is based on the measurement of polarisation current I_p during the charging time t_{ch} and measurement of the depolarisation current I_{dp} during the short circuit period t_{sc}. Analysis of dielectric response data in the time domain can be based on calculation of the conductivity σ (S/m), polarisation index (*PI*) or conductivity factor (*CF*) values. Measurement of the conductivity over a long period of time may reflect the DC conductivity, and is thus most affected by localised defects in the insulation. However, computation of conductivity necessitates knowledge of the geometry

capacitance or dielectric permittivity of the test object. In addition, conductivity is a temperature dependent parameter. Conductivity can be estimated using the following equation.

$$\sigma = \frac{\varepsilon_0}{C_0 U_{\mathrm{ch}}}\left(I_{\mathrm{p}}(t) - I_{\mathrm{dp}}(t)\right) \tag{4.1}$$

where C_0 is the geometrical capacitance, U_{ch} is the charging voltage i_p and i_{dp} are the polarisation and depolarisation currents.

The temperature independent parameter *PI* is calculated using following equation.

$$PI = \frac{R_{600}}{R_{60}} = \frac{I_{\mathrm{p}60}}{I_{\mathrm{p}600}} \tag{4.2}$$

where R_{60} and R_{600}, and $I_{\mathrm{p}60}$ and $I_{\mathrm{p}600}$ are the resistance and polarisation currents at 60 and 600 seconds.

Another method that combines both polarisation and depolarisation current data is the conductivity factor CF. The conductivity factor indicates the change in insulation conductivity [10 and 11].

$$CF = \frac{\sigma_{30\mathrm{s}}}{\sigma_{60\mathrm{s}}} = \frac{i_{\mathrm{p}}(30s) - i_{\mathrm{dp}}(30s)}{i_{\mathrm{p}}(60s) - i_{\mathrm{dp}}(60s)} \tag{4.3}$$

The conductivity factor is the ratio of conductivity evaluated from the polarisation and depolarisation currents at 30 and 60 seconds. With this method of analysis it is possible to avoid the use of parameters that are temperature and geometry dependent. In addition, CF is independent of the charging voltage.

The degree of nonlinearity can be used as diagnostics criteria for XLPE insulation, and may be calculated as [13, 15 and 68]:

$$\psi = \frac{I_{\mathrm{D}}(U)_{20\,\mathrm{sec}}}{I_{\mathrm{Da}}(U_a)_{20\,\mathrm{sec}}} \tag{4.4}$$

where ψ is the nonlinearity factor and I_{Da} is the depolarisation current caused by the lowest charging voltage U_{a} (e.g. 1 kV), and I_D is the depolarisation current caused by the charging voltage U. The choice of 1 kV for the lowest charging voltage U_{a} is based on practical experience which showed that even heavily water treed XLPE cables remained linear at voltages up to 1 kV [15]. Current values measured 20 s after the start of depolarisation are used to calculate the linearity factor. A nonlinearity factor of $\psi = 1$ corresponds to linearity, while $\psi > 1$ indicates a non-linear response [9].

4.1.2 Frequency domain dielectric response measurement

In the frequency domain the dielectric response appears as the dissipation factor *tanδ* at certain frequencies or frequency ranges, and as the total harmonic distortion in the loss current at power frequency.

In the frequency domain, the amplitude and phase of both the applied sinusoidal voltage U_A and current I_M through the test object are measured at different frequencies in order to obtain the impedance *Z(ω)*. Figure 4.2 shows a pointer diagram of such a measurement, where I_M is the total current through the insulation, I_R is the resistive current through the insulation and I_C is the capacitive current through the insulation.

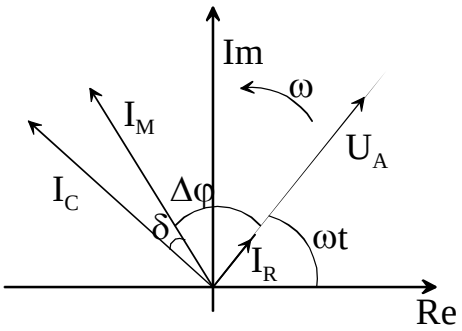

Figure 4.2 Pointer diagram.

Diagnostic parameters such as the complex permittivity $\varepsilon^*(\omega)$ or complex capacitance $C^* = \varepsilon^*(\omega) \cdot C_0$ are calculated from the impedance *Z(ω)*

$$Z(\omega) = \frac{U(\omega)}{I(\omega)} = \frac{1}{j\omega C_0 \varepsilon^*(\omega)} \tag{4.5}$$

where $\varepsilon^*(\omega) = \varepsilon' - j\varepsilon''(\omega)$ is the complex permittivity and C_0 the geometric capacitance of the test object. Knowledge of the impedance allows calculation of the dissipation factor tanδ. For practical purposes the dissipation factor is calculated as

$$\tan\delta(\omega) = \frac{I_R}{I_C} = \frac{\sin(\delta)}{\cos(\delta)} = \frac{\varepsilon''(\omega)}{\varepsilon'(\omega)} \tag{4.6}$$

Measurement of *tanδ* for assessing the condition of insulation is preferable from a practical point of view because it is independent of the geometry of the test object, and should not depend on the applied voltage in the case of sound and good insulation. However, it does not contain as much information as either the real ε' or the imaginary ε'' parts of the complex permittivity [9].

For the diagnostics criteria it is stated that the minimum value of the dissipation factor *tanδ* contains information about the moisture content of oil-paper insulation [13, 14 and 15]. It is suggested that the moisture content of oil-paper insulated cables could be estimated using the

following expression [13, 16 and 46], where *mc* is moisture content in percent and $tan\delta_{min}$ is the minimum value of the measured dissipation factor over the frequency range.

$$mc = 15{,}3 + 2{,}53 \cdot \ln(\tan \delta_{\min}) \tag{4.7}$$

However, other studies have shown that this statement may not be true for field aged oil-paper insulated cables. It could be that degradation by-products are polarised and their response may overcome the moisture response [17 and 18].

XLPE insulation diagnostic criteria are based on the non-linearity of the dielectric response in the frequency domain with respect to the charging voltage. In the frequency domain, non-linearity is characterised by a voltage dependent dissipation factor, whereas in the time domain, a greater than proportional increase of the response occurs with an increase in charging voltage. Non-linearity in the dielectric response has been the subject of study in many doctoral theses [5, 13, 19 and 20].

4.2 Fourier transformed infrared analysis

The infrared portion of the electromagnetic spectrum is divided into three regions; the near-, mid- and far- infrared, named for their relation to the visible spectrum. The mid infrared region lies between 2,5 – 25 μm, which corresponds to the wavenumbers 4000 – 400 cm^{-1}. The wavenumber is a measure used in FITR-spectroscopy. FTIR spectrums can be used to characterise and identify materials, to monitor chemical reactions and to determine the absence or presence of specific chemical groups [22].

A molecule gives a signal in IR spectroscopy if there is a change in dipole moment during a vibration, which means that molecules having asymmetric bonds are IR activated [21]. Simple molecules have only one bond, which may stretch. More complex molecules may have many bonds, which can vibrate several different ways like symmetrical and asymmetrical stretching, scissoring, rocking, wagging and twisting.

Fourier transform infrared (FTIR) spectroscopy is a measurement technique for collecting infrared spectra. Instead of recording the amount of energy absorbed when the frequency of the infra-red light is varied (monochromatic), the IR light is guided through an interferometer. After passing the sample the measured signal is known as the interferogram. Performing a mathematical Fourier Transform on this signal results in a spectrum identical to that obtained from conventional infrared spectroscopy.

In photoacoustic spectroscopy (PAS) a sample is illuminated with a modulated beam emerging from the interferometer. At wavelengths where the sample absorbs some fraction of the incident radiation, a modulated thermal fluctuation will be generated. This modulated heating of the sample causes a pressure variation of the gas in the photoacoustic cell and thus produces a signal, which is detected by a microphone of high sensitivity [21].

Figure 4.3 shows an example of an FTIR spectrum measured from an XLPE insulation sample. Peaks in the spectrum corresponding to different wavenumbers indicate the presence of different chemical compounds in the insulation material. Qualitative interpretation of an FTIR spectrum can be a difficult task if the sample contains several chemical compounds. Qualitative

interpretation demands a strong understanding of chemistry. FTIR spectrums can be also interpreted quantitatively. In this method, which is used to find possible compounds in unknown samples, the unknown spectrum is compared to known spectrums to find out similarities or differences between spectrums. Tables containing different chemical compounds with their corresponding vibration wavenumbers are available to aid interpretation.

For example, the oxidation level in XLPE insulation can be detected from the IR absorbance of the carbonyl groups lying in the 1690 – 1745 cm^{-1} range [23]. The existence of excess carbonyl groups and double bonds in the deteriorated region of XLPE insulation strongly suggest the occurrence of chain scission and free radical formation [42].

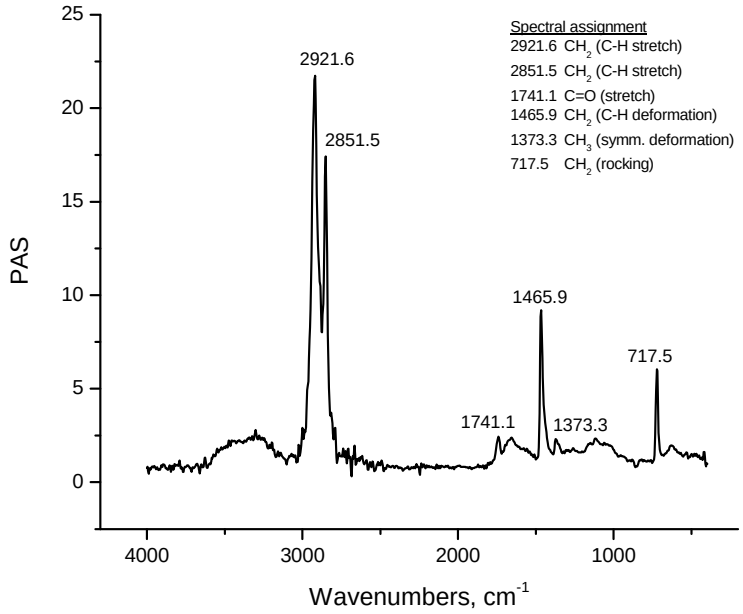

Figure 4.3 An example of FTIR-spectrum measured from XLPE-insulation.

4.3 Needle testing

A needle test will provide comparative breakdown data but not the degree of correlation with actual in-service performance. Needle testing can be applied for short cable samples – a sample length of about 10 cm is enough. For this type of testing it is important to select a test procedure that provides consistent and reproducible conditions of electrical stressing. Selected needle testing is based on the ASTM D 3756-97 standard [24].

The test procedure involves placing a well defined sharp needle electrode inside the insulation at a predetermined depth. Figure 4.4 shows the test setup for needle testing. A needle with a tip radius of 2±1 μm is inserted into the insulation using a needle drive. Before insertion, the needle must first be washed with alcohol to remove foreign particles and then silicon oil should be applied to the tip of the needle. The purpose of the silicon oil is to fill up any microcracks that might be introduced to the insulation while inserting the needle. A voltage is then applied to needle. The conductor of the test cable is grounded during this procedure. Initially the step

voltage is linearly increased with a steepness of 500 V/s up to 4 kV. Then the voltage is increased step by step until breakdown occurs. The magnitude of step is 1 kV and the duration 1 minute. The same procedure has been used in previous studies and showed that differences in insulation performance can be detected by needle testing [25]. The applied voltage and time to breakdown were recorded for future analysis. Needle test results can be analysed using various statistical methods. Figure 4.4 shows the test set up for needle testing. Voltage is applied to the needle and the cable conductor is grounded.

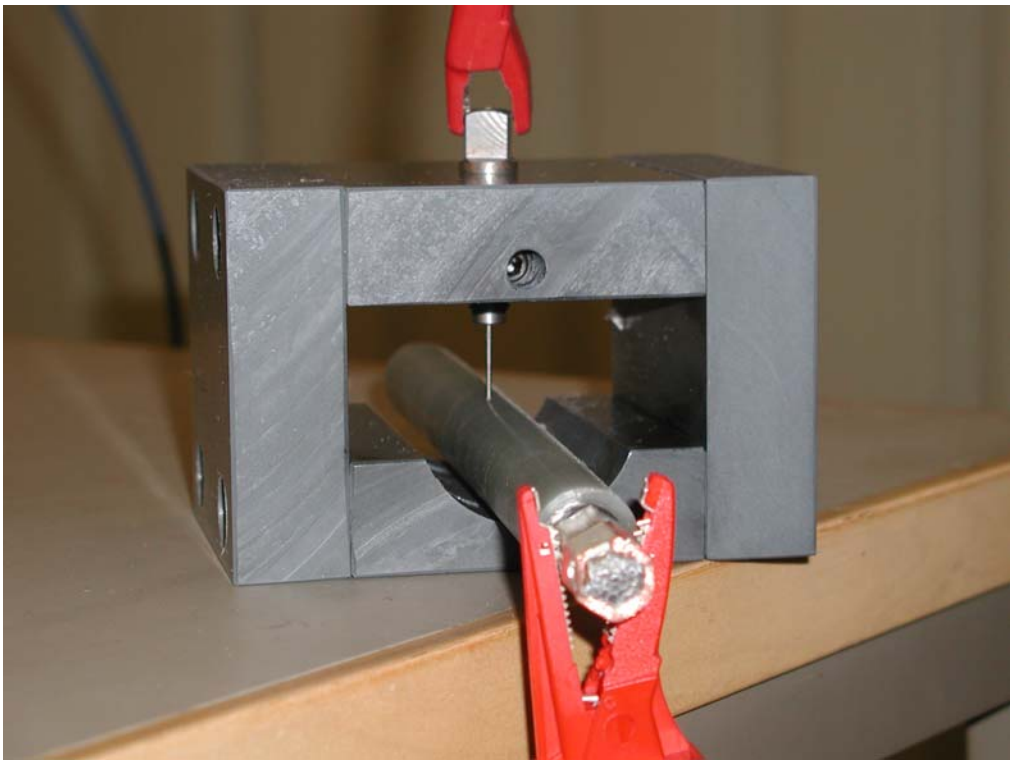

Figure 4.4 Needle test set up.

4.4 Breakdown testing

In this procedure, test cables are subjected to breakdown testing in order to evaluate their remaining voltage withstand levels. The outer jacket, metallic sheath or wires and outer semiconductive layer are stripped from about 85 centimetres from each end of the cable. Aluminium semi rings are inserted to smooth the electric field at the ends of the semiconductive screen. The cable ends are inserted into specially made oil-filled cable terminations. Figure 4.5 shows the cable termination used during the breakdown testing.

The test voltage used in this thesis is generated by a 300 kV high voltage transformer. The test voltage is connected to one end of the cable under test. Measurement of the test voltage is made using a capacitive voltage divider and a computer aided measuring program. At the beginning of the test, the voltage is increased to the nominal voltage level (U_o) of cable. The voltage is maintained at this level for a period of five minutes. After this, the voltage is increased in steps of U_o until breakdown occurs. The duration of each step is five minutes. A similar breakdown test protocol has also been used in other studies [7].

Figure 4.5 Oil-filled cable termination used during the breakdown testing.

4.5 Degree of polymerisation

The degree of polymerisation of new insulating paper is around 1100 – 1300. Degradation of paper will cut cellulose molecules and reduce the degree of polymerisation. A degree of polymerisation of less than 500 indicates significant thermal degradation. Paper has completely lost its mechanical strength when the degree of polymerisation goes below 200.

There are many methods available to determine the average molecular weight of a paper sample. Standards ASTM D 4243, IEC 60450 and SCAN-CM 15:99 [29, 30 and 49] describe standardised methods to evaluate the degree of polymerisation of insulation paper. The method described herein determines the intrinsic viscosity and the value obtained is referred to as the average viscometric degree of polymerization. In order to measure the viscosity of a cellulose sample it must first be dissolved in a suitable solvent.

A sample of the cellulose is degreased with hexane in a Soxhlet extractor, dried, and conditioned in a humidity controlled environment. A weighed sample of the cellulose is then dissolved in a cupriethylene-diamine solution by tumbling it into a sealed flask with glass balls. The dynamic viscosity of the resulting solution is determined and by comparing it with the viscosity of the cupriethylene-diamine solvent, one can calculate the intrinsic viscosity and the average viscometric degree of polymerization.

The average viscometric degree of polymerization represents the average number of glucose units in the cellulose polymer and these values can range from 800 to 1600 units, with the most probable value being about 1200. As the paper undergoes ageing, these polymer chains degrade into smaller units. If the paper is subjected to a severe fault such as overheating or arcing, the polymers will also be degraded. As shorter length chains are formed, this lowers the average

degree of polymerization. Thus, this method allows one to assess the condition of the cellulose insulation within the unit. Since these values represent averages, when evaluating a sample of cellulose it should be compared to a fresh sample of the same origin.

4.6 Moisture content analysis

There are several methods, such as infrared reflection spectrometry, gas chromatography and microwave spectroscopy, available for moisture determination. All these methods require complex apparatus to perform the analysis. The most commonly used methods to determine moisture content from insulation paper are the drying method and the titration method. The majority (99,0 % - 99,9 %) of the moisture is in the paper and only a very small portion in the oil. The amount of free oil in medium voltage cables is limited, so moisture content is determined from paper samples rather than the oil.

Moisture inside the insulation paper is vaporised out when using drying methods. The weight of the paper sample is measured before insertion into a drying oven. After a certain time, the weight of the paper sample is measured again. The difference in weight determines the moisture content. There are some disadvantages in this method. In principle, the loss in weight due to drying is determined, which is not necessarily the same as the water content. Apart from water, other volatile components in the sample may also be removed. It also takes a long time to obtain the analytical results [31]. Sometimes a sample must be in the drying oven for several hours.

In contrast to drying, titration is a specific method. Titration is an analytical technique which allows the quantitative determination of a specific substance (analyte) dissolved in a sample. It is based on a complete chemical reaction between the analyte and a reagent (titrant) of known concentration which is added to the sample. The titrant is added until the reaction is complete. In order to be suitable for a determination, the end of the titration reaction has to be easily observable. This means that the reaction has to be monitored (indicated) by appropriate techniques, e.g. potentiometry (potential measurement with a sensor) or with colour indicators. The measurement of the dispensed titrant volume allows the calculation of the analyte content based on the stoichiometry of the chemical reaction. The reaction involved in a titration must be fast, complete, unambiguous and observable.

The most well known titration method to determine water content is called Karl Fischer titration. With Karl Fischer titration both free and bound water can be determined. The method works over a wide concentration range, from a ppm level up to 100 %, and supplies reproducible and correct results [31]. There are several national and international standards available concerning determination of water content by Karl Fischer titration [32, 33 and 34].

4.7 Tensile strength and elongation at break

Strength of material refers to the ability to resist loads without failure because of excessive stress or deformation [35]. The chemical degradation of XLPE insulation will make it more brittle, and this phenomenon may be detected by tensile strength measurements.

The tensile strength of a material is the ratio of the maximum load a material can support without fracture, when being stretched, to the original area of cross section of the material. When stresses less than the tensile strength are removed, a material completely or partially returns to its

original size and shape. As the stress approaches that of the tensile strength, a material that has begun to flow forms a narrow, constricted region that is easily fractured. Tensile strengths are measured in units of force per unit area. Elongation is the amount of uniaxial strain at the point of fracture.

5 Experimental tests on field aged XLPE cables

Experimental tests were carried out on field aged XLPE insulated medium voltage cables. Field aged cable samples were collected from one electric utility. The idea was to collect cables with different design, age, environmental conditions and loading. The design of the cables is well known as is their age. The environmental conditions are quite well known, at least at the level of the installation environment, but the loading conditions and knowledge of the history of the cables are not so well known. In general, the loading on the cables has been moderate.

The hypothesis put forward with respect to the XLPE insulated cables is that degradation of field aged cables can be detected applying chemical analyses and electrical measurements, and that cable age should have a correlation with these electrical measurement results and chemical analyses. The electrical measurements and tests were performed in the high voltage laboratory and the chemical analyses in the forest product laboratory.

5.1 Cable samples

A summary of tested XLPE cables is shown in Table 5.1. All tested cables were 10 kV cables, except 50 and 32, which were 20 kV cables.

Table 5.1 Tested XLPE cables. Tests: PDC dielectric response in time domain, FTIR Fourier transform infra red spectroscopy, NT needle test and BD breakdown test. Additional tensile strength and elongation at break tests were carried out on cables number 1, 2, 3, 4, 6, 8, 12 and 50.

Cable ID number	Type	Installation year	Tests
1, 3	AHXCMK 3x95 / 70	1995	PDC, FTIR, NT, BD
2, 4, 8	AHXDMK 3x50 / 16	1980	PDC, FTIR, NT, BD
5, 7, 9, 10	AHXDMK 3x50 / 16	1980	PDC, FTIR, BD
6	AHXDMKG 3x120 / 25	1980	PDC, FTIR, NT, BD
12	HXCMK 3x35	1977	PDC, FTIR, NT, BD
32	AHXAMK-W	1996	NT
36	AHXCMK 3x95 / 70	1977	FTIR,BD
37, 38, 40, 41	AHXDMK 3x50 / 16	1977	FTIR, BD
39	AXKJ 3x120 / 25	1977	FTIR, BD
42, 44	AHXDMK 3x95 / 25	1977	FTIR,BD
46, 47, 48	AHXDMK 1x630 / 50	1977	FTIR
50	AHXAMK-W	Reference	PDC, FTIR, NT

The tested cables were installed and operated in good environmental conditions. The cables were installed on cable racks in ducts and the loading of the cables had been rather steady. A new cable manufactured in 2006 was used as a reference test object.

The field aged cables represent two different kinds of basic construction. Cables 1, 3, 6, 36 and 39 had helically wound copper wires around all three phases. Individual grounding of phases was not used. A watertight metal laminate is not present in this type of cable. The other field aged cables had individual copper foil around each phase, except the reference cable 50 and cable number 32, which had aluminium laminate around each phase. A uniform metallic foil around the cable insulation will provide a watertight barrier against moisture. Figures 5.1 and 5.2 show a constructional view of the two main cable types investigated here.

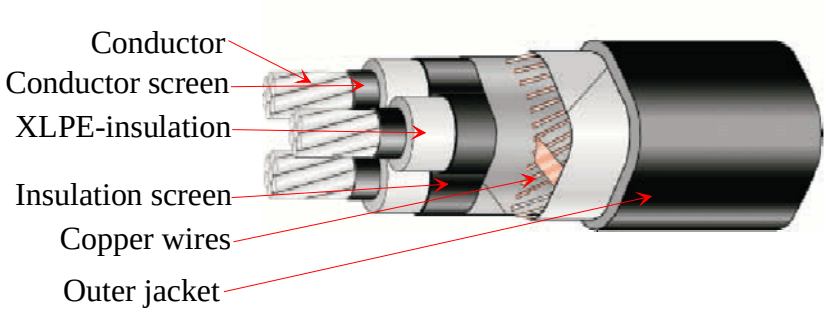

Figure 5.1 Construction of AHXCMK (AXJK) type cable.

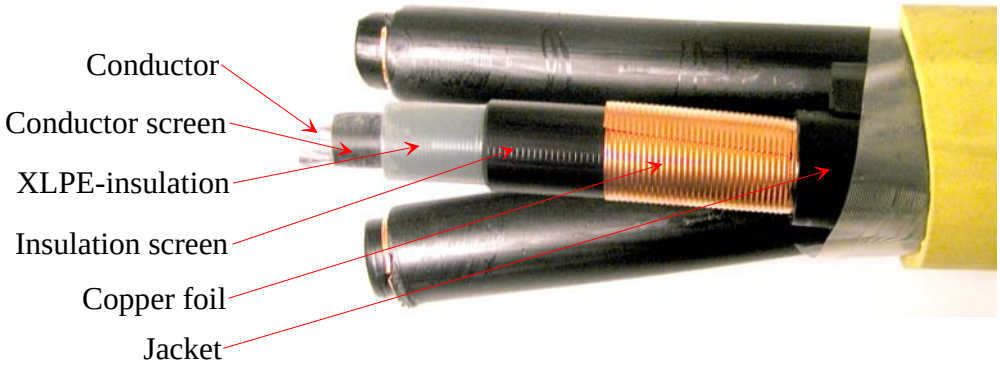

Figure 5.2 Construction of AHXDMK type cable.

5.2 Dielectric response in time domain

Time domain dielectric response PDC-measurements were carried out on each phase of the cable samples. The ends of the cables that had not been used for terminations were stripped for the measurements. Each measurement was carried out using an insulation resistance meter. The + terminal of the insulation resistance meter was connected to the cable conductor and the – terminal to the grounding of the cable. The guard terminal of the insulation resistance meter was left open. The effect of an additional guard electrode on the cable terminations was checked and did not show significant deviation from measurement without the guard electrode. For the simplicity of the measurement set up, guard electrodes were not used.

The measurement voltage was 5 kV. The polarisation current was measured during the voltage application. The voltage was applied for a period of ten minutes. The depolarisation

current was recorded during the one minute short circuit time. The measured values were stored for further analysis.

The measured polarisation current values for each cable sample were below the measurement capability of our measuring instrument. The polarisation current measurement limit was reached within thirty seconds from the application of the charging voltage. In many cases, even negative polarisation current values were measured. Calculation of condition parameters such as the PI or CF indices is not reasonable in such cases.

An example of a PDC measurement result on cable 1L1 is shown in Figure 5.3. Polarisation current values are low, even sometimes negative, and depolarisation current values are also low. It was impossible to rank the test cables in different condition classes with PDC-measurement results. Degradation of cable insulation was not detected on these cable samples using time domain dielectric response measurements.

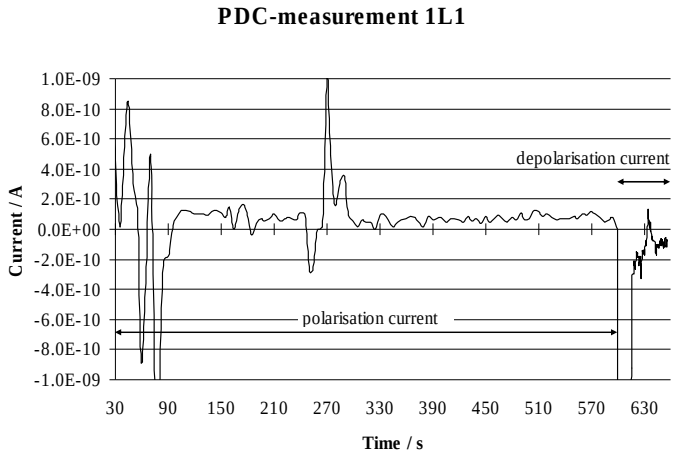

Figure 5.3 Example of a PDC-measurement result on XLPE-cable.

5.3 Fourier transformed infrared analysis

Baseline correction and normalisation to the C-H stretch band at wavenumber 2923 cm^{-1} were performed for all spectra shown in this section. Baseline correction is applied by subtracting the average value of the wavenumbers from 1900 to 2400 cm^{-1} from each response wavenumber. The response of wavenumber 2923 cm^{-1} is set to be 10 units during normalisation, as shown in Figure 5.4. The FTIR spectrum of an unused cross-linked polyethylene sample taken from cable 50 is shown in 5.4. The bands at ca. 2923, 2852, 1466, 1369 and 720 cm^{-1} correspond to the characteristic vibration modes of saturated CH_2 structures in polyethylene. In addition to these vibrations, the weak bands at 3600-3200 cm^{-1} and at 1740 cm^{-1} indicate the presence of a small number of hydrogen bonded hydroxyl groups and carbonyl structures, respectively. These bands are typical for non-aged cross-linked polyethylene samples, due to polymer degradation during processing and residues of cross-linking additives [39].

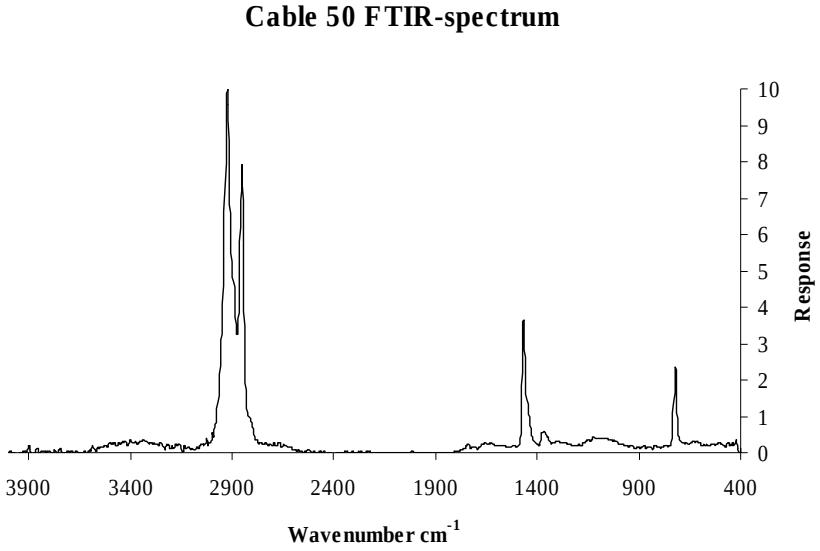

Figure 5.4 Baseline corrected and normalised FTIR spectrum of cable sample 50.

Oxidation of XLPE insulation is one of the major degradation mechanisms. From the FTIR spectrums it is possible to evaluate the oxidation level. The carbonyl index reveals information on the polymer reaction with oxygen. There are several different ratios which can be assessed to determine the oxidation level. For example, the following band ratios can be used to determine the carbonyl index: 1710 cm^{-1} and 1470 cm^{-1}, 1710 cm^{-1} and 1380 cm^{-1}, 1724 cm^{-1} and 1898 cm^{-1}, 1735 cm^{-1} and 1369 cm^{-1} [2, 39 and 40]. Calculation of the carbonyl index is based on the effect oxidation has on the spectral region around wavenumbers 1710 – 1740 cm^{-1} (the carboxyl stretching band). This region is compared to a region where oxidation has little or no effect. Different carbonyl index values are shown in Table 5.2. Calculation of the ratio between wavenumbers 1724 and 1898 cm^{-1} was not reasonable because responses at wavenumbers 1898 cm^{-1} were negative. The Pearson correlation factor between different carbonyl indices varies from 0,46 to 0,83. Calculation of the Pearson correlation factor showed that the correlation between cable age and cable carbonyl index is week, lower than 0,2 in all cases.

The FTIR spectra from the different cable samples revealed some differences in their chemical structure. Table 5.2 shows that the carbonyl indices of cables 3, 8, 37, 46 and 48 indicate a high level of oxidation. The FTIR spectrums of these cables and the new cable, number 50, are shown in Figure 5.5. It can be seen that the relative intensities of the characteristic polyethylene bands were similar in all samples. However, ageing clearly increased the hydroxyl and carbonyl stretching bands at ca. 3300 cm^{-1} and 1740 cm^{-1}, respectively. The high wavenumber of the carbonyl band indicates an increased content of aldehyde groups and possibly ester groups, while ketones, which are typical oxidation products of polyethylene, would have an absorption band at ca. 1714 cm^{-1} where no remarkable changes were observed. On the other hand, the band height at 1651 cm^{-1} also seemed to vary in these samples, which can be explained by the presence of conjugated carbonyls in the samples. These changes are more clearly seen in the zoomed spectrums shown in Figure 5.6.

Table 5.2 Carbonyl indices.

ID	Index A 1735/1369	Index B 1710/1470	Index C 1710/1380	Age		ID	Index A 1735/1369	Index B 1710/1470	Index C 1710/1380	Age
1	0,36	0,049	0,45	11		37	0,58	0,064	0,47	29
2	0,40	0,042	0,46	26		38	0,44	0,048	0,43	29
3	0,53	0,073	0,84	11		39	0,40	0,062	0,41	29
4	0,30	0,049	0,36	26		40	0,38	0,046	0,39	29
5	0,43	0,036	0,29	26		41	0,40	0,054	0,42	29
6	0,21	0,027	0,26	26		42	0,30	0,045	0,38	29
7	0,47	0,058	0,37	26		44	0,34	0,046	0,38	29
8	0,53	0,037	0,45	26		46	0,61	0,065	0,50	29
9	0,32	0,040	0,30	26		47	0,51	0,048	0,41	29
10	0,52	0,025	0,19	26		48	0,56	0,066	0,54	29
12	0,47	0,084	0,66	29		50	0,39	0,044	0,44	1
36	0,38	0,040	0,34	29						

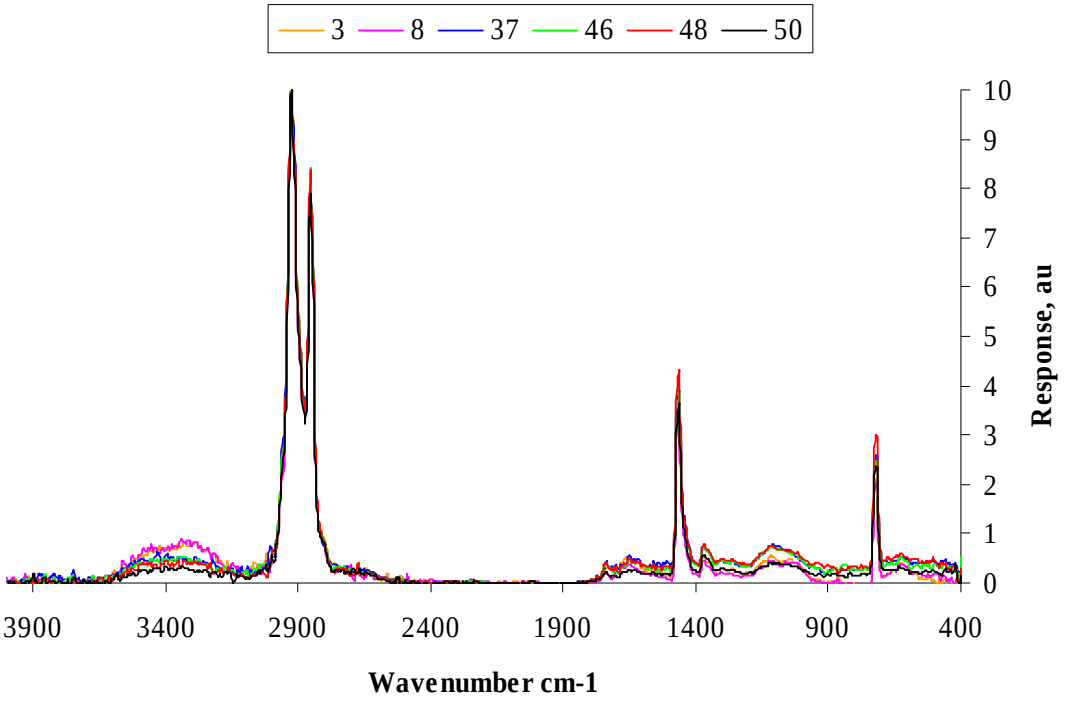

Figure 5.5 FTIR spectrums of new cable 50 and used cables 3, 8, 37, 46 and 48.

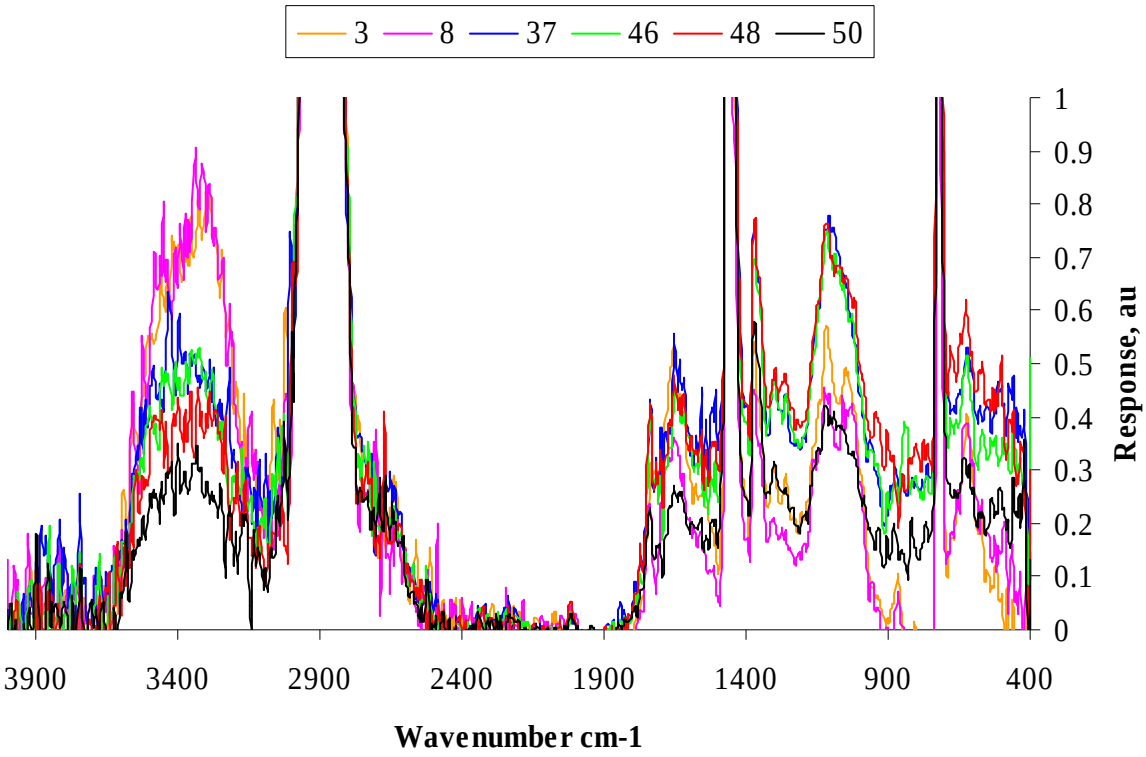

Figure 5.6 Zoomed FTIR spectrums of new cable 50 and used cables 3, 8, 37, 46 and 48.

Chemical changes in XLPE insulation caused by degradation can be detected using FTIR analysis. Changes were rather small but nevertheless clearly detectable. The carbonyl index is linked to the oxidation of cable insulation. Since the age of a cable does not significantly affect carbonyl index values, the carbonyl index can be directly linked to the degradation degree of insulation. Carbonyl index values can rank cables into different condition classes.

5.4 Needle testing

Needle breakdown tests were carried out on cable numbers 1 – 4, 6, 8, 12, 32 and 50. Ten short cable samples from each cable were tested. The aim of the testing was to test a 2 mm thick insulation layer from each cable sample. A sharp needle was inserted into the cable insulation using a fine needle driver and the deepness of the needle was regulated with a dial indicator. In the needle test, the maximum electric field strength E_{max} at the applied test voltage U will be:

$$E_{\max} = \frac{2U}{r \cdot \ln\left(\frac{4d}{r}\right)} \tag{5.1}$$

where r is the tip radius and d is the insulation thickness.

The basic statistical results from the needle tests are shown in Table 5.3. Calculations are based on N measurement results, variation from ten results means that breakdown voltage levels were sometimes higher than 31 kV. In Table 5.3, the cables are sorted according to the average

breakdown voltages. Calculation of the maximum electric field strength is based on the assumption that the tip radius of the needle is 1,5 μm and the insulation thickness is 2 mm.

It can be clearly seen from the results that the breakdown voltage in the needle test and cable age has no correlation. The Pearson correlation factor for cable age and average breakdown voltage is 0,39, showing weak positive correlation. The difference between the highest and lowest average breakdown voltage values is only 18,5 %.

Table 5.3 Needle test breakdown voltage results, sorted according to average breakdown voltage level.

Cable	N	Age	Average kV	Standard deviation kV	Median kV	Minimum value kV	Maximum value kV	Maximum electric field strength MV/mm
2	10	26	24,81	4,32	25,50	18,97	30,00	3,86
12	10	29	24,08	3,34	24,00	18,94	29,00	3,74
1	9	11	23,31	3,64	24,34	15,93	27,67	3,62
8	10	26	22,80	4,12	23,11	15,97	29,02	3,54
32	10	9	22,20	5,18	20,68	14,73	29,51	3,45
4	8	26	22,19	6,06	22,46	13,46	31,34	3,45
50	10	1	21,33	3,75	19,49	17,00	27,77	3,31
3	10	11	20,87	5,15	19,92	13,48	28,35	3,24
6	10	26	20,22	4,63	20,44	14,94	25,86	3,14

Evaluation of cable performance based on average breakdown voltage level may be incorrect. Cable insulation is only as strong as its weakest point. This means that one or two high breakdown voltage measurement results do not have a significant influence on the overall performance of the cable if low breakdown voltages are measured correctly. If we assume that the measurements are reliable and one out of ten tests is performed close to the weakest point of the cable insulation, the results can be sorted according to the minimum value of breakdown voltage. Results based on the minimum value of breakdown voltage are shown in Table 5.4.

Table 5.4 Needle tests results sorted according to minimum value of breakdown voltage.

Cable	Minimum kV	Age	Metallic screen type
2	18,97	26	Copper foil
12	18,94	29	Copper foil
50	17,00	1	Aluminum laminate
8	15,97	26	Copper foil
1	15,93	11	Copper wires
6	14,94	26	Copper wires
32	14,73	9	Aluminum laminate
3	13,48	11	Copper wires
4	13,46	26	Copper foil

The Pearson correlation factor of 0,24 indicates that there is weak correlation between the minimum value of breakdown voltage and cable age. New unused cable number 50 is in a higher position when cables are sorted according to the minimum value of breakdown voltage.

One problem associated with the comparison of measurement results using breakdown voltages in kilovolts is that the time to breakdown is not considered. A breakdown measurement can be analysed using the breakdown energy as a product of test voltage and test time. Table 5.5 shows results based on the calculation of breakdown energy. Ranking of cables is almost identical to Table 5.4. The Pearson correlation factor for age and the minimum value of breakdown energy is 0,22.

Table 5.5 Needle test results sorted according minimum breakdown energy in kVmin.

Cable	Minimum kVmin	Average kVmin	Standard deviation kVmin	Median kVmin	Maximum kVmin
2	173,8	299,2	97,7	309,3	432,7
12	163,4	269,8	73,0	266,1	388,0
50	131,8	212,6	87,3	172,9	372,2
1	116,0	285,3	102,0	267,9	482,5
8	114,0	246,0	90,4	244,4	386,4
32	102,8	235,5	105,3	195,6	389,8
6	94,4	196,8	91,1	188,2	313,5
4	79,9	247,7	131,1	249,6	474,9
3	77,3	210,7	108,1	180,5	383,7

It seems that it is impossible to rank cables into different condition classes with direct comparison of measurement results. The differences between cables seem to be small. Statistical analysis can be used for evaluation if there are differences between cable test results.

The Mann-Whitney test is a two-sample rank test of the equality of two population medians. The Mann-Whitney test hypotheses are: H_0: the median of population 1 equals the median of population 2 versus H_1: The medians of populations 1 and 2 are different. The Mann-Whitney test assumes that the data are independent random samples from two populations that have the same shape and a scale that is continuous, or ordinal if discrete.

The Kruskal-Wallis test is a test of the equality of medians for two or more populations. The Kruskal-Wallis hypotheses are: H_0: there are no differences between the medians of the samples versus H_1: there is a difference between the medians of the two samples. An assumption for this test is that the samples from the different populations are independent random samples from continuous distributions, with the distributions having the same shape.

The Kruskal-Wallis test result is the probability of the difference between the data sets occurring by chance. The Kruskal-Wallis test result for all needle test breakdown voltage results is 0,431. Since it is higher than 0,05, the H_1 hypothesis must be rejected and the H_0 hypothesis accepted. According to the Kruskal-Wallis test result, there is no reason to conclude that the overall medians differ for the tested cable samples. This does not mean that the medians are the same. There is just no evidence that the overall medians differ.

The Mann-Whitney test results for different cable pairs are shown in Table 5.6. The Mann-Whitney test result value is the actual probability of the differences occurring by chance. The only comparison pair where test value is lower than 0,05 is cables 2 and 6. With this pair, hypothesis H_0 must be rejected and hypothesis H_1 accepted. The Needle test result medians of cables 2 and 6 are different. Results from the other pairs do not give any reason to conclude that the overall medians differ. Once again, this does not mean that the medians are the same, but that there is just no evidence that they differ.

Table 5.6 Mann-Whitney test results for cable pairs.

Cable	1	2	3	4	6	8	12	32	50
1	1,00								
2	0,44	1,00							
3	0,35	0,08	1,00						
4	0,87	0,31	0,79	1,00					
6	0,15	**0,03**	0,68	0,38	1,00				
8	0,71	0,34	0,38	0,91	0,31	1,00			
12	0,84	0,43	0,16	0,52	0,08	0,57	1,00		
32	0,84	0,31	0,62	0,79	0,38	0,73	0,52	1,00	
50	0,31	0,09	0,68	0,97	0,34	0,47	0,12	0,68	1,00

The statistical analysis has shown that there is only a discernible difference between cables 2 and 6. These cables are of the same age but different design. Cable 2 has a copper foil and cable 6 has helically wound copper wires. The design of a cable may have a small effect on insulation performance, but otherwise it is clear that the needle tests could not clearly rank the test cables into different condition classes.

In the needle test, we can say that it is the maximum electric field strength that determines the breakdown phenomena. The maximum electric field strength is several orders higher than the average electric field strength. For example, if we assume that the insulation thickness is 2 mm, the needle tip radius is 1,5 μm and the test voltage level is 22 kV, the maximum electric field according equation 5.1 is 3420 kV/mm and average electric field strength is 11 kV/mm. Microscopic imaging of the test needles showed that variation in the tip radius is negligible. Insertion of the needle into the cable insulation will cause uncertainty in the measurement results. If we assume that the total uncertainty in the insulation thickness d is 1 mm, meaning that the real insulation thickness varies from 1 mm to 3mm, the maximum electric field strength varies from – 4,5 % to 8,8 % from its nominal value. The total uncertainty may contain factors such as the bending of the cable and needle, the thickness of the insulation and conductor screen, the asymmetry of the insulation, etc. Variations are smaller than the standard deviation of the measured breakdown voltages.

5.5 Breakdown testing

Breakdown testing was carried out on cable numbers 1 – 10, 12, 36 – 42 and 44. All three phases of the cables were tested separately. In total, 57 breakdown tests were performed. At the beginning of the test the voltage was raised to the nominal phase to ground voltage level (U_o) of cable. The voltage was maintained at this level for a period of five minutes. After this, the

voltage was increased in steps of U_o until breakdown occurred. The duration of each step was five minutes. The withstand levels from the breakdown testing are shown in Figure 5.7. The withstand levels varied from 5 times U_o up to 14 times U_o. Cable 6L2 was tested up to a voltage level of 15 times U_o, and because breakdown did not occur at this level, testing was stopped. The reason for stopping the test was that continuing would have meant that the expected withstand levels of the test termination would have been exceeded. The withstand level of new XLPE insulated cable is at least 25 – 30 U_o [38].

The mean value of withstand levels was 8,04 U_o and the standard deviation was 2,43 U_o. The withstand levels of helically wound copper wire cable designs were higher than the mean value of breakdown voltage. The copper foil cables withstand levels were lower than the mean value, except for the withstand levels of cables 4 and 12. The results clearly indicate that there is no correlation between cable service age and breakdown voltage. The Pearson correlation factor for cable service age and breakdown voltage level is -0,30. Results show that the cable design may have an effect on voltage withstand performance. One explanation for the weaker performance of the copper foil type cables could be the indentations on the outer semiconductive layer caused by the copper foil. These indentations were observed over the whole length of these cables, and might cause local electric field enhancements leading to early breakdown.

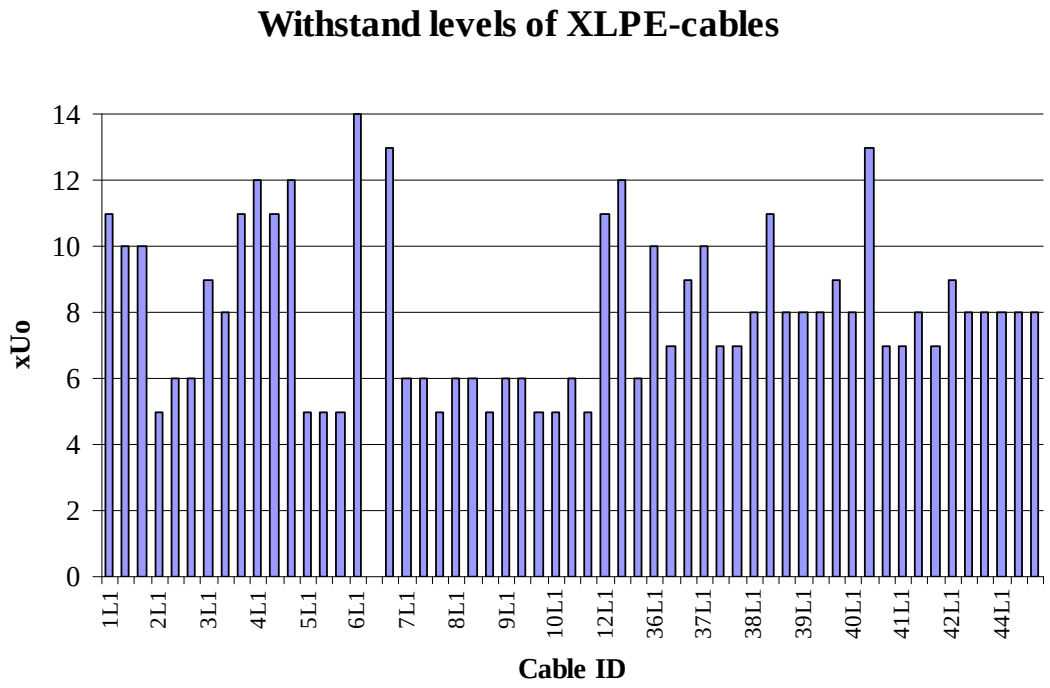

Figure 5.7 Breakdown test withstand levels of the tested cables.

5.6 Tensile strength

Tensile strength measurements were carried out on cables 1, 2, 3, 4, 6, 8, 12 and 50 at the cable laboratory of Prysmian Cables and Systems Oy. Insulation samples were taken from one phase of each cable. Six insulation samples were taken from the cable samples and determination of

tensile strength was repeated six times. Tests were carried out according to the IEC 60811-1-1 standard [36]. The median values of the tensile strength and elongation at break are shown in Table 5.7.

Table 5.7 Tensile strength and elongation at break results.

	1	2	3	4	6	8	12	50
Tensile strength N/mm^2	25,7	26,2	27,0	25,0	27,3	26,7	17,5	25,0
Elongation %	531	518	547	537	545	525	552	483

According to IEC 60502-2, the standard requirements for new cables are as follows. The tensile strength should be more than 12,5 N/mm^2 and the elongation at break should be more that 200 % [37]. All the tested cables fulfilled these requirements. The results show that only the cable number 12 is significantly different to the others. This could be an indication of chemical degradation causing the development of brittleness in the cable insulation.

5.7 Combined results and discussion on XLPE insulation

The results from the different diagnostic methods that were applied show clearly that even when the condition of cables differs, the measurable differences are rather small. All analyses showed that degradation of cable insulation is not related to cable age. Exogenous degradation processes such as thermal degradation, rather than self degradation, play a more significant role in overall degradation.

Table 5.8 summarises the diagnostics measurement results for cables 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12 and 50. A variety of diagnostics analyses were performed on these cables. The dielectric response measurement results are ignored, because the results from the different cables did not differ from each other. Correlation factors were calculated between different parameter pairs. Most of the cases showed a correlation of less than 0,5 between each pair.

The carbonyl content effect on the performance of polymer insulation depends on the stresses affecting the insulation. The initiation mechanism of the deteriorated region and electrical tree caused by AC stress varies depending on the presence of the oxygen [42]. The existence of excess C=O (carbonyl group) and C=C double bonds suggest the occurrence of chain scission and free radical formation. In oxygen free conditions the direct attack of accelerated carrier or UV light on polymer may form a number of chain scissions at low density in a relatively large region during long time of AC voltage application [42]. This gradual decomposition is considered to form many small voids and destroy the lamellar structure [42]. In oxygen rich conditions, main scission occurs successively from the first broken chain by auto oxidation, possibly forming large voids, which is considered to be origin of the electrical tree channel [42].

In a needle test a deteriorated region (increased carbonyl content) in polyethylene increases the treeing resistance for AC ramp voltages and positive impulse voltages [42]. The changes of polyethylene structure in the deteriorated region may be responsible for this [42]. Deteriorated areas can improve insulation performance locally. Electron microscopic observation has shown

many small voids and cracks in the deteriorated region and the lamellar structure of polyethylene is destroyed in the deteriorated region of the insulation [42]. The number of chain scissions is accumulated at low density during long periods of AC voltage application in the deteriorated region, forming small voids and destroying lamellar structure [42].

The partial discharge lifetimes of polyethylene will decrease when the carbonyl content is above a certain threshold limit. The discharge lifetime is determined primarily by the chemical structure of the polymer and the concentration of the carbonyl [43]. Carbonyl groups enhance the free radical formation and hereby accelerate the surface erosion of micro cavities, causing early partial discharge breakdown [43].

According to results from reference [45] the increased oxidation of microtomed XLPE-samples increases their breakdown strength up to certain point. This appears to be compatible with the modified free volume theory of breakdown. .According to this theory, breakdown is associated with the longest electron trajectory in micro-vacuoles, which comprise the polymer's free volume [45]. It seems that oxidation either has a tendency to reduce the mean dimension of the micro-vacuoles or that it influences electron ballistics, perhaps by enhanced charge trapping at polar moieties such as carbonyl groups [45]. From these results it seems that increased carbonyl content can even improve insulation performance at some stresses up to a certain point. Increased carbonyl content will have an effect on the long time performance of polymer insulation by decreasing the AC voltage withstand level.

Table 5.8 Summary of results obtained from different diagnostics analyses. A, B and C are different carbonyl index values. Sheath types: H is helical wound copper wire, T is copper foil and Al is aluminium laminate.

ID	Age	A	B	C	Needle test Breakdown voltage [kV]	Needle test Breakdown energy [kVmin]	Withstand voltage [kV]	Tensile strength [N/mm^2]	Metallic screen type
1	11	0,36	0,049	0,45	23,31	116,0	59,9	25,7	H
2	26	0,43	0,042	0,46	24,81	173,8	29,0	26,2	T
3	11	0,56	0,073	0,84	20,87	77,3	54,1	27	H
4	26	0,39	0,049	0,36	22,19	79,9	67,7	25	T
5	26	0,48	0,036	0,29	-	-	29,0	-	T
6	26	0,21	0,027	0,26	20,22	94,4	78,3	27,3	H
7	26	0,47	0,058	0,37	-	-	32,9	-	T
8	26	0,53	0,037	0,45	22,80	114,0	32,9	26,7	T
9	26	0,41	0,04	0,30	-	-	32,9	-	T
10	26	0,52	0,025	0,19	-	-	29,0	-	T
12	29	0,47	0,084	0,66	24,08	163,4	56,1	17,5	T
50	1	0,39	0,044	0,44	21,33	131,8	-	25,0	Al

Figure 5.8 shows the logarithmic correlation plot between carbonyl index A and withstand voltage. The correlation coefficient for the logarithmic fit was 0,58. On these samples, the withstand voltage decreased according to equation 5.2 when carbonyl index A increases.

$$y = 19{,}44 - 30{,}03 \cdot \ln(x) \qquad (5.2)$$

According to the relation between the carbonyl index A and withstand voltage level it can be said that FTIR analysis and calculation of the carbonyl index can be used as a diagnostics measure of cable insulation condition. In these cable sample results the carbonyl index A is linked to the most important insulation property, voltage withstand level at service voltage stress.

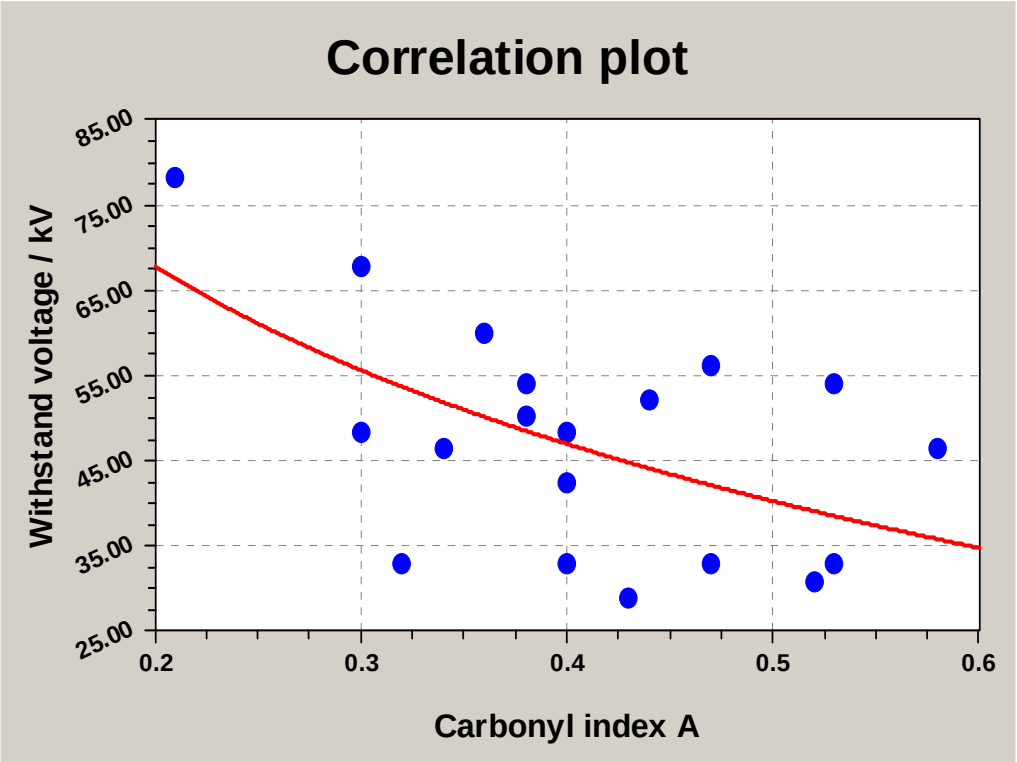

Figure 5.8 Correlation between carbonyl index A and the withstand voltage of XLPE-cables.

For future applications, it could be recommended that during the repair of cables after failure, cable insulation samples should be taken for FTIR analysis. FTIR analysis and calculation of the carbonyl index is quite easy to perform and the results should give a good estimation of overall cable condition.

Table 5.9 shows the evaluation of carbonyl index A values according to cable condition classes. The carbonyl index values in Table 5.9 are based on correlation equation 5.2 shown above. The criteria of the very bad class was chosen to be a voltage withstand level less than 2 *Uo*, because in medium voltage networks, extended overvoltages up to 1,9 *Uo* may occur during earth faults. Earth fault overvoltages may cause sudden cable failure or initiate the fast development of irreversible cable insulation degradation.

Table 5.9 Evaluation of carbonyl index A values in terms of cable condition classes based on the correlation equation between carbonyl index A and voltage withstand levels.

	Good	Moderate	Poor	Very bad
Voltage withstand level	> 5 Uo	5 Uo – 3 Uo	3 Uo – 2 Uo	< 2 Uo
Carbonyl index A	< 0,70	0,70 – 1,00	1,00 – 1,30	> 1,30

Experimental test data clearly supports the finding that cables having carbonyl index values less than 0,6 belong to the cable class good. The other cable classes presented in Table 5.9 have been obtained by extrapolating the experimental test data according to equation 5.2. This is the first approach to combine FTIR analysis results to real full scale withstand voltage testing results. The results found in the literature are from smaller insulation samples.

It is clear that a certain uncertainty is included in the shown results. Insulation samples used in the FTIR-analysis are taken only from one point in the insulation. The sample was taken from middle radial section of the insulation. The representativeness of the insulation sample contains uncertainty. Carbonyl content varies when insulation samples taken from inner, middle and outer sections are analysed [61]. Samples were analysed using the FTIR method two to four times. Thus the analysis result contains uncertainty. The background noise level of the measurements can vary between analyses. As can be seen from Figure 5.8, logarithmic correlation between the carbonyl index A and voltage withstand level is moderate. Change of data, e.g. due to a larger number of test samples, could change the curve fitting from logarithmic to some other form. Extrapolation of these functions could lead to different boundaries between the different cable condition classes. Field aged XLPE-cables having carbonyl indices higher than 0,6 and belonging to other cable condition classes than good could not be found during this research program.

In this study the number of cables investigated was limited. Further study with a higher number of test cables would give more a precise picture of the usability of this method. The tested cables had been installed in good environments; they were installed on cable racks in cable tunnels. The temperature, humidity and loading of the cables had been rather steady. Only two types of cable designs were represented. The oldest cable tested was 29 years old (installed in 1977). These cables represent some of the oldest XLPE cables in use in Finland.

Even though the research was carried out on a limited number of test samples, this method looks promising for getting a general overview of cable insulation condition. The FTIR method is destructive, which means that is the only reasonable time to collect insulation samples is during the repair following a cable failure. Previous studies have shown that the condition assessment of cable systems should be based on more than one measurement method [44]. Results obtained from FTIR analysis should be verified with some other method before taking severe practical actions. Other methods, such as partial discharge and dielectric response measurements, should be used on a regular basis to analyse the condition of cable systems in use that are nearing the end of their service life or have otherwise been subject to severe loading or environmental conditions.

The procedure for applying the FTIR method is quite simple. As mentioned, the repair of cable failure is a natural point to collect insulation samples for FTIR analysis. The jointing of a cable requires stripping and cutting off the insulation. A minimum of two turns of stripped insulation spiral is required for the FTIR-analysis. Insulation turns for analysis should be carefully taken from the insulation spiral avoiding any contact with the fingers.The insulation sample should be stored in a clean glass bottle, which should be sealed airtight. Sample bottles should be kept in a dry, dark and cool environment. Samples should be sent for analysis within two weeks.

FTIR-analysis results need to be manipulated before calculation of the carbonyl index value. Direct calculation of carbonyl index values is not possible because the background noise of the measurement varies between measurements. The following steps are needed for carbonyl index calculation.

- Measurement of FITR spectrums – at least two spectrums per sample are needed
- Averaging of spectrums. Spectrums must be added together and divided by the number of spectrums.
- Base line correction. The average value of wavenumbers 1900 to 2400 cm^{-1} is subtracted from each wavenumber response.
- Calculation of the carbonyl index by dividing the response at wavenumber 1735 cm^{-1} by the response at wavenumber 1369 cm^{-1}.

Estimation of cable condition can be based on the carbonyl index A value and the condition classes given in Table 5.9.

It seems that thirty years in a good environment is not enough time to indicate the overall long term performance of XLPE insulation. According to the findings related in this chapter, the studied XLPE insulated cables were in good condition. More tests on older cables are needed in the future to clarify the long term performance of deteriorated XLPE-insulation.

6 Experimental tests on oil-paper insulated cables

Experimental tests were carried out on field aged oil-paper insulated medium voltage cables. The field aged cable samples were collected from electric utilities. The idea was to collect cables with different design, age, environmental conditions and loading. The design of the cables was well known as was their age. Environmental conditions were quite well known, at least at the level of installation environment. The loading conditions and the history of the cables were not so well known. In general, the cable loadings had been moderate.

Electrical measurements and tests were performed in the high voltage laboratory and the chemical analyses in the forest product laboratory.

6.1 Test cables

As mentioned, the test cables were collected from different utility companies. Core type and belt type cables were tested. In core type cables, the phases have individual main insulation and metallic jacketing. In belt type cables, the phases have individual insulation, but an additional common layer of belt insulation and metallic jacketing.

The 10 kV PLKVJ and APAKM cables are common belt type cables installed in Finnish networks. The 20 kV HPLKVJ, PYLKVJ and APYAKMM cables are common core type cables still in use. The oldest cable tested was installed in 1955 and the newest ones in 1977. The tested cables are shown in Table 6.1. Figures 6.1 and 6.2 show examples of the construction of belt and core type cables.

All the tested cables had been removed from normal use, but none of the cables had suffered breakdown or any other major electrical fault. Some of the cables were damaged by external causes before being taken out of service.

Table 6.1 Tested oil-paper cables.

Cable ID	Age	Type		Cable ID	Age	Type
11	29	APYAKMM		25	40	APAKM
13	29	APYAKMM		26	51	PLKVJ
14	29	APYAKMM		27	31	APYAKMM
15	29	APYAKMM		28	31	APYAKMM
16	29	APYAKMM		29	31	APYAKMM
17	42	PNLKVg		51	42	PLKVJ
18	42	PNLKVg		52	42	PLKVJ
19	42	PNLKVg		53	42	PLKVJ
20	39	PLKVJ		54	33	APAKM
21	34	APYAKMM		55	33	APAKM
22	34	APYAKMT		56	33	APAKM
23	34	APYAKMT		59	42	PLKVJ
24	41	APYAKMT				

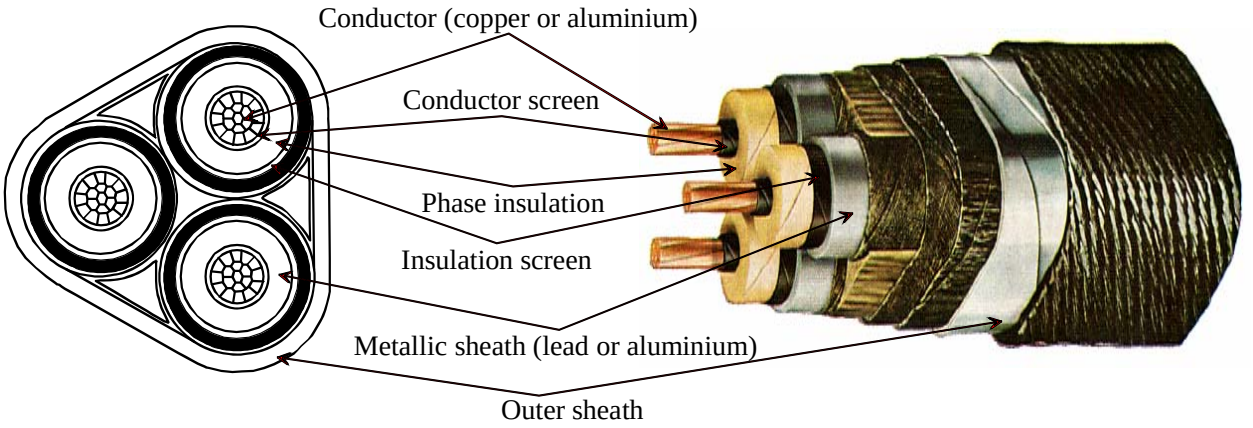

Figure 6.1 Example of the construction of a core type medium voltage oil-paper insulated cable (PYLKVJ cable).

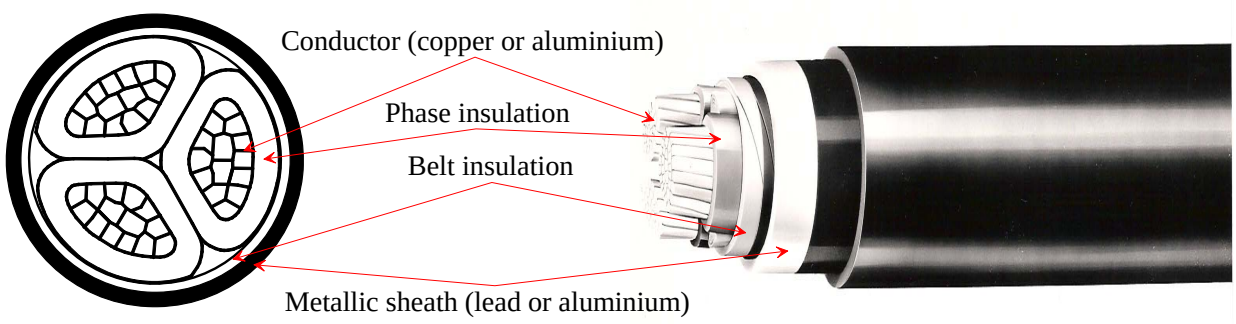

Figure 6.2 Example of the construction of a belt type medium voltage oil-paper insulated cable (APAKM cable).

6.2 Dielectric response in the time domain

Dielectric response measurements were carried out in a similar way as for the XLPE-cables. The measuring voltage was 5000 V, the charging time ten minutes and the short circuit time one minute. Guard connection was not used. Measurement was carried out between the conductor and metallic jacket. Phases not under measurement were connected together and to the metallic jacket in the belt type cables.

Figure 6.3 shows an example of PDC measurement results on two different cables. Responses are scaled with the measured capacitance value so that they can be compared with each other. From figure 6.3, it can be seen that the final polarisation current value of cable 15L1 is three decades higher than the polarisation current of cable 53L3. This directly means that the insulation resistance of cable 15L1 is lower than the insulation resistance of cable 53L3. Another observation from Figure 6.3 is that the polarisation current of cable 15L1 is steady during the

charging period, whereas the polarisation current of cable 53L3 decreases during the charging time.

The polarisation index PI-values were calculated by dividing the polarisation current values measured at the ten minutes point with polarisation current value measured at the one minute point. The PI-index values varied between 0,56 and 6,35. The measured depolarisation current values can be used for the calculation of the conductivity factor CF-values. The conductivity factor values varied between 0,582 – 2,013.

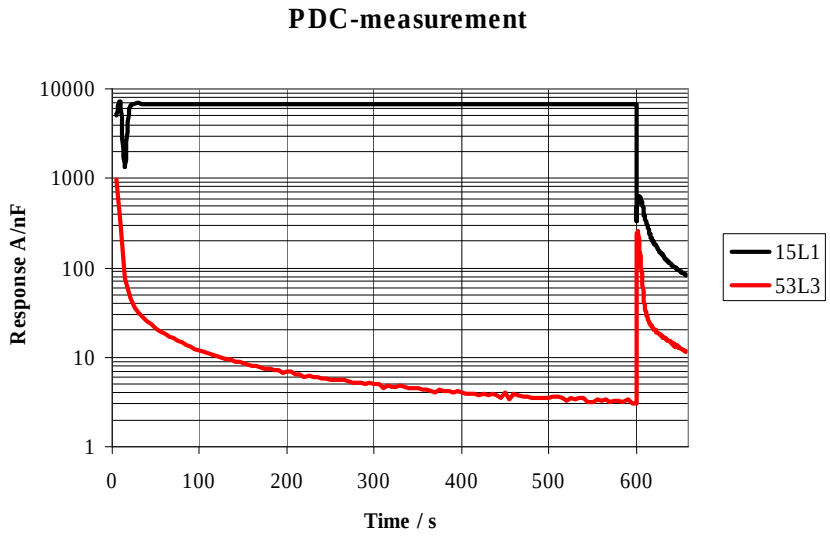

Figure 6.3 Example of PDC-measurement results from two different cables – the polarisation current up to 600 seconds and the depolarisation current afterwards

The conductivity of the cable insulation can be estimated from the polarisation current using the following equation.

$$\sigma = \frac{\varepsilon_0}{C_0 U_0} i_p(t) \tag{6.1}$$

The conductivity can be also be estimated by using the depolarisation current values together with the polarisation current values, according to equation 6.2.

$$\sigma = \frac{\varepsilon_0}{C_0 U_0} \left[i_p(t) + i_{dp}(t) \right] \tag{6.2}$$

Conductivity values varied between $4{,}34 \cdot 10^{-11}$ to $1{,}24 \cdot 10^{-14}$ S/m using equation 6.1 and between $4{,}29 \cdot 10^{-11}$ to $1{,}45 \cdot 10^{-15}$ S/m using equation 6.2. Conductivity values calculated using equations 6.1 and 6.2 have an almost perfect linear correlation with each other.

Figures 6.4 and 6.5 show the calculated PI-index and CF-index values as a function of cable age. It can be seen from Figures 6.4 and 6.5 that variation of the PI-index and CF-index values is large even though the cables are the same age. Correlation between the calculated PI and CF-

index values and cable age is weak. Correlation calculations even show positive correlation which is quite unexpected. This means that PI and CF-index values are higher on older cables. This can partly be explained by a change in the cable designs. Cables older than 40 years are mainly belt type cables with copper conductors and free moving oil impregnation. Cables less than 40 years old are mainly core type cables with aluminium conductors and high viscosity mass impregnation. These properties, especially the conductivity of the insulating oil, may have had an effect on the measurement results. The characteristics of different types of impregnating oils were not included in this study.

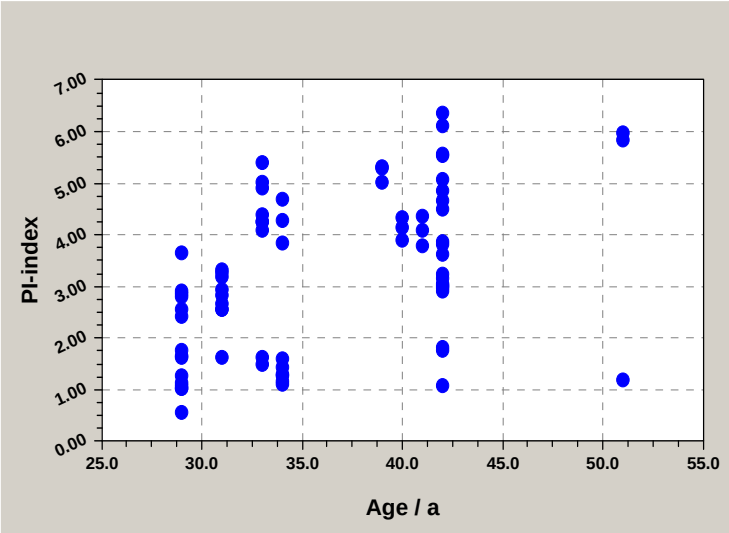

Figure 6.4 Calculated PI-index values as a function of cable age.

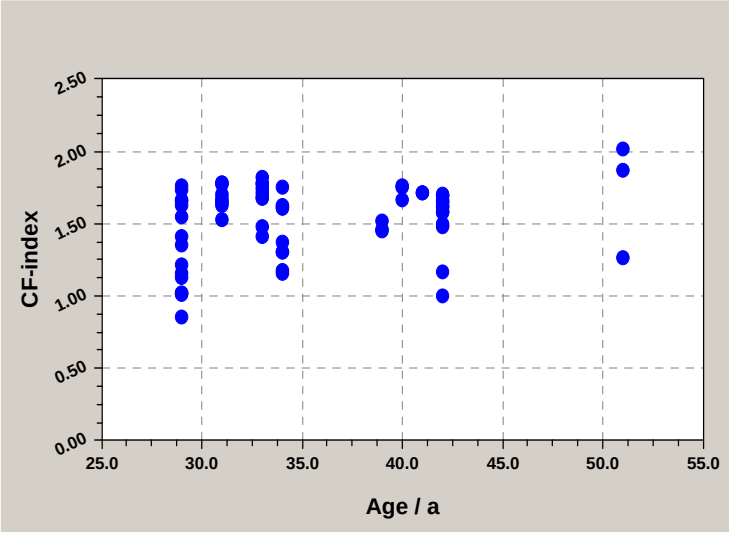

Figure 6.5 Calculated CF-index values as a function of cable age.

Figure 6.6 shows a correlation plot between the PI-index and CF-index values. Good nonlinear correlation can be found. The correlation curve plotted in Figure 6.6 follows the equation $y=ab^{1/x}$, with constants a=1,856 and b=0,639.

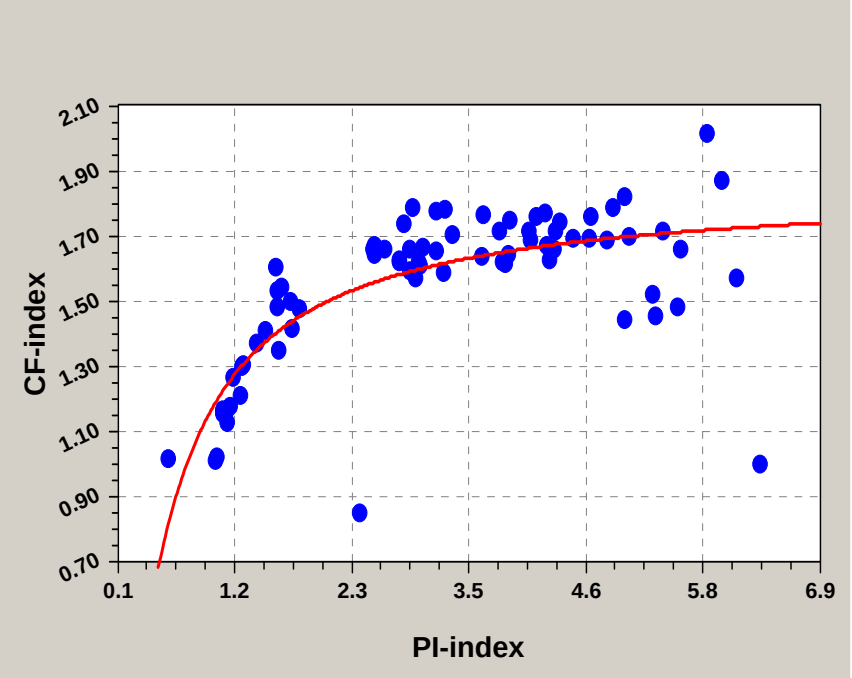

Figure 6.6 Correlation between the PI and CF indices.

6.3 Dielectric response in frequency domain

Dielectric response measurements were carried out using a 200 V peak excitation with variable frequency, starting from 1000 Hz and going down to 0,01 Hz. Figure 6.7 shows a measurement result from cables 15L3 and 24L3 having different loss factor minimum values. Figure 6.8 shows FDS-measurement results as a function of cable age. It can be seen that the correlation between loss factor minimum value and cable age is weak.

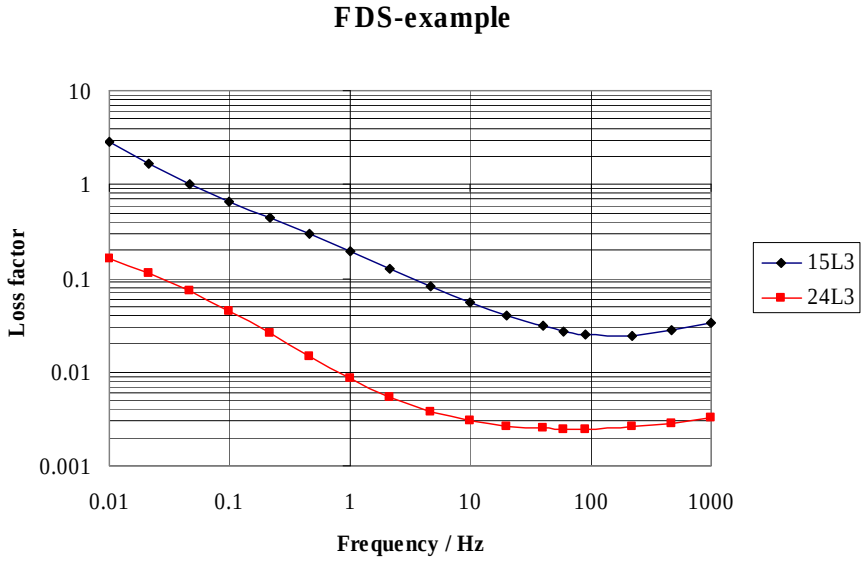

Figure 6.7 Example of FDS-measurement.

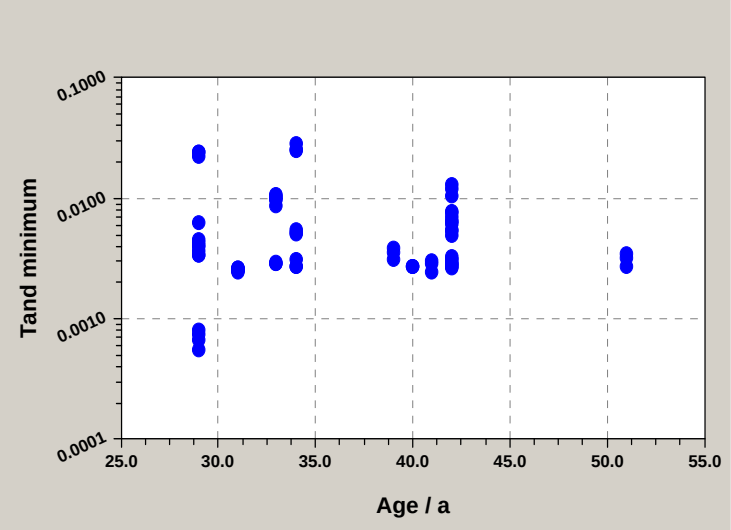

Figure 6.8 FDS-measurement results as a function of cable age.

Comparison of time and frequency domain dielectric response measurement results showed that direct correlation between time and frequency domain results is weak. A logarithmic correlation between the loss factor minimum and the estimated conductivity was found, as shown in Figure 6.9. The correlation equation is $y = a + b\ln(x)$, with constants a = 0,079 and b = 0,002.

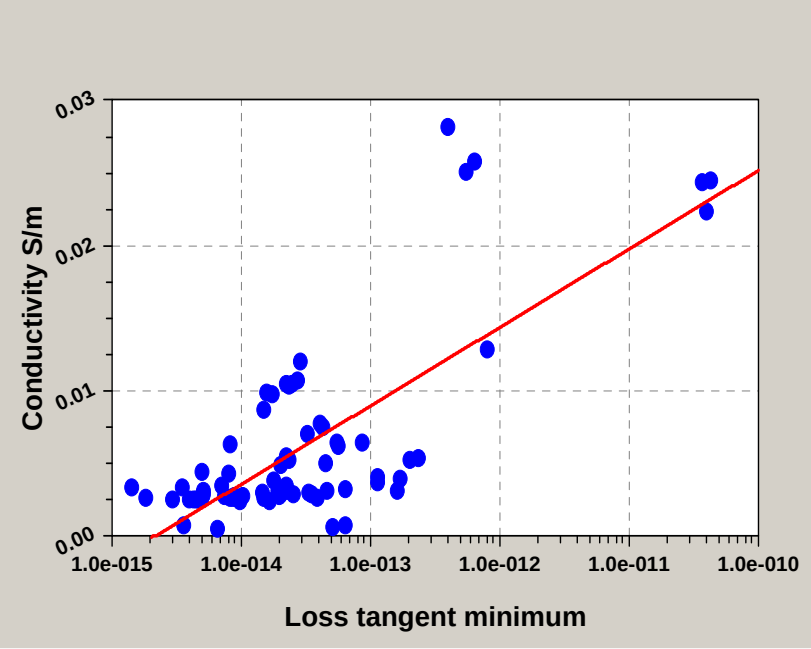

Figure 6.9 Correlation curve between loss tangent minimum and conductivity.

6.4 Moisture content of insulation paper

Paper samples for the moisture content analysis and degree of polymerisation determination were taken from the middle of the paper insulation thickness. The moisture contents of paper samples were determined using the drying method. The samples were weighed before they were

placed in the drying oven. The samples were dried at a temperature of 130ºC. The total drying time was three hours. Temperature and time selections were based on the empirical knowledge of the paper laboratory. After drying, the paper samples were weighed again. Table 6.2 shows the moisture content analysis results.

As can be seen from Table 6.2, the moisture contents of paper samples are sometimes confusing. Sample number 21L1 even gave a negative value during the first measurement set. It can be stated that if a moisture content analysis result shows values less than 0,2 %, externally or internally generated moisture is not present, as the initial moisture content of cable insulation during the manufacturing of a cable would have been 0,2 % or more. Overall, all cable samples were quite dry.

Table 6.2 Moisture content of analysed cable samples.

Set 1				Set 2				Set 3		
Cable	Age	Moisture w%		Cable	Age	Moisture w%		Cable	Age	Moisture w%
11L1	29	0,27		22L3	34	0,38		51L1	42	1,07
13L2	29	0,32		23L3	34	0,34		52L2	42	0,81
15L1	29	0,40		24L1	41	0,49		53L3	42	1,12
16L2	29	1,60		25L3	40	0,24		54L3	33	0,06
17L2	42	1,93		26L1	51	0,75		55L2	33	0,17
18L2	42	0,05		27L3	31	0,01		56L3	33	0,28
19L1	42	0,19		28L2	31	1,00		59L1	42	0,51
21L1	34	-0,41		21L1	34	0,04		21L1	34	0,20
20L2	39	0,27		29L3	31	0,33		New	-	6,41
								Crepe	-	6,60

Figure 6.10 shows the correlation plot between moisture content and cable age. It is clear that there is no correlation between cable age and moisture content.

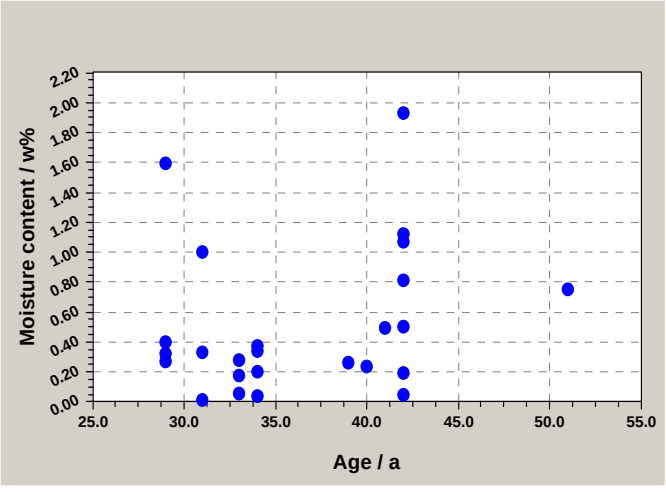

Figure 6.10 Correlation plot between cable age and moisture content.

6.5 Degree of polymerisation

Paper samples were taken from the middle of the insulation paper thickness. In the case of transformer insulation it has been stated that the degree of polymerisation may vary depending on the sample location. The degree of polymerisation is lowest at the hottest points, e.g. near the conductor. With these cables, paper samples were taken from the middle of the insulation to represent the average condition of the cable insulation. On the other hand, these cables have been subject to quite steady and moderate loading conditions, normally less than 50% of the rated load.

Measurement of viscosity was carried out according to standard SCAN-CM 15:99 [49]. Various equations are given to describe the relation between viscosity and the degree of polymerisation [49]. In this study, the DP-values were calculated from the corresponding viscosity values η [ml/g] using the formula $DP = -81{,}28 + 1{,}574 \cdot \eta$. This formula is based on the viscosity and DP values taken from the Tervakoski materials laboratory report [50].

Before viscosity measurement, the impregnating liquid needed to be washed out of the paper samples. In the case of mass impregnated cables, this was found to be quite a challenging task. Paper samples were immersed in a hexane solution before viscosity measurement. Different procedures were tested. In the first paper sample test set, the hexane solution was changed twice, each submersion lasting twenty minutes. The second set involved three soaking periods of twenty minutes plus a final period of one hour, each time in a new hexane solution. The third set had five immersion periods, each period with a new hexane solution lasting twenty minutes. Then the hexane extraction samples were dried at room temperature overnight and the dry solid content was determined by drying the samples for two hours at a temperature of 130ºC.

The dissolution times of paper samples were longer than stated in the standard. The first test set of paper samples were submerged in water for four days and in the CED-solution for four hours. The second and third test sets were kept in water for seven days and in the CED-solution overnight. These dissolution times gave quite good solutions without any or only a minor amount of sediment. The viscosity was determined from two parallel samples. The average value was taken to be the viscosity of the sample.

Measured viscosity values and calculated DP-values are shown in Table 6.3. All the measured cable insulation paper samples showed a DP-value equal or higher than the new paper sample. The new paper sample was insulation paper used in power transformer insulation. Basically, the DP-value or paper used in cables is similar to paper used in transformers, but variation in the chemical pulp used in paper manufacturing can affect the degree of polymerisation. The chemical treatments can also have an effect on DP-value [57]. All measured DP-values are quite high, so it is evident that the mechanical properties of insulation paper are not a limiting factor at the present time for the cables from which these paper samples were taken.

Table 6.3 Viscosity and DP values of paper samples.

Set 1					Set 2					Set 3			
Cable	Age	η	DP		Cable	Age	η	DP		Cable	Age	η	DP
11L1	29	688	1002		20L2	39	799	1176		29L3	31	814	1200
13L2	29	790	1161		22L3	34	977	1457		51L1	42	892	1323
15L1	29	936	1392		23L3	34	981	1463		52L2	42	945	1406
16L2	29	909	1349		24L1	41	964	1436		53L3	42	806	1187
17L2	42	761	1115		25L3	40	980	1461		54L3	33	934	1389
18L2	42	805	1186		26L1	51	962	1433		55L2	33	918	1364
19L1	42	687	1000		27L3	31	859	1271		56L3	33	1007	1504
21L1	34	901	1337		28L2	31	824	1216		59L1	42	901	1337
					21L1	34	970	1446		21L1	34	933	1387
										Paper	New	687	1000
										Crepe	New	866	1282

Figure 6.11 shows the correlation plot between cable age and DP-value. It is clearly seen that there is no correlation between age and DP-value. Even in new paper insulation the DP-value can vary depending on paper quality, paper batch and heat treatments before jacketing. It seems clear that the degradation processes causing a decrease in DP-value were not yet evident on these cables.

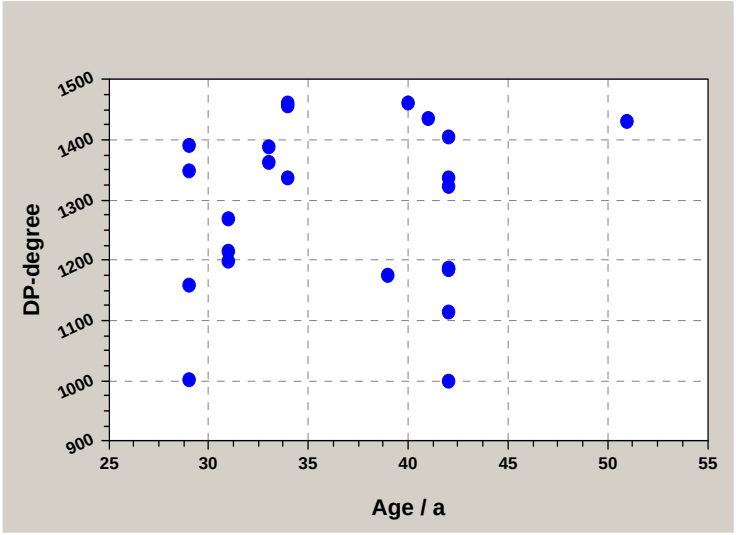

Figure 6.11 Correlation plot between cable age and DP-value.

6.6 *Fourier transformed infrared analysis*

FTIR analyses on the paper samples taken from the field aged cables were performed using the same photo acoustic spectroscopy measuring systems as were used on the XLPE cable samples. Baseline correction was made on all average spectrums shown in this section. Average spectra were formed by averaging two to four measured spectra collected from the same sample. The band between wavenumbers 1900 – 2400 cm^{-1} was used for baseline correction. Figure 6.12 shows an example of FTIR-spectra measured from a oil-paper sample (black curve) and on a paper sample without impregnation (red curve). The effect of the impregnation oil on the FTIR spectra can be clearly seen.

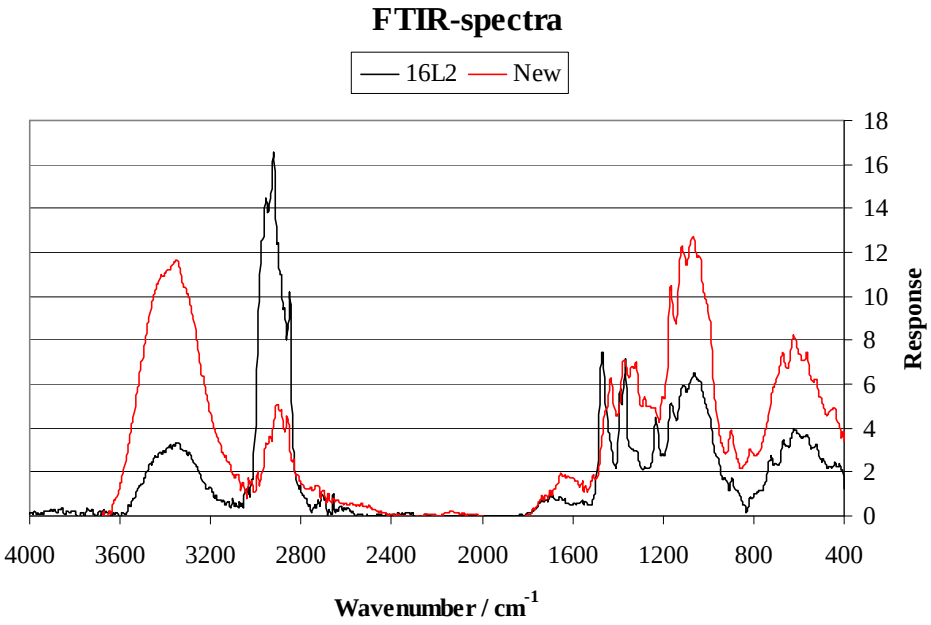

Figure 6.12 FTIR-spectra from an oil-paper sample (black curve) and paper sample without impregnation oil (red curve).

A liquid water molecule has three natural vibration frequencies. On the FTIR spectra these vibrations occur at wavenumbers 1644, 3280 and 3490 cm^{-1} [51]. An increase in the amount of water in paper insulation should be revealed by an increased absorption of water molecule vibration wavenumbers. The problem is that impregnation oil and cellulose $(C_6H_{10}O_5)_n$ will also have an effect on FTIR spectra. Typically, the cellulose O-H vibration will occur in the band between wavenumbers 3500 and 3650 cm^{-1}. The vibration of carboxylic acid, typical for oil, occurs in the band between wavenumbers 1690 and 1760 cm^{-1}. Both bands are quite near to typical water molecule vibration frequencies and can disturb FTIR spectral analysis. Figure 6.13 shows the measured spectras from all the cable insulation samples. Figure 6.13 also shows the wavenumber bands of interest in cable insulation condition analysis.

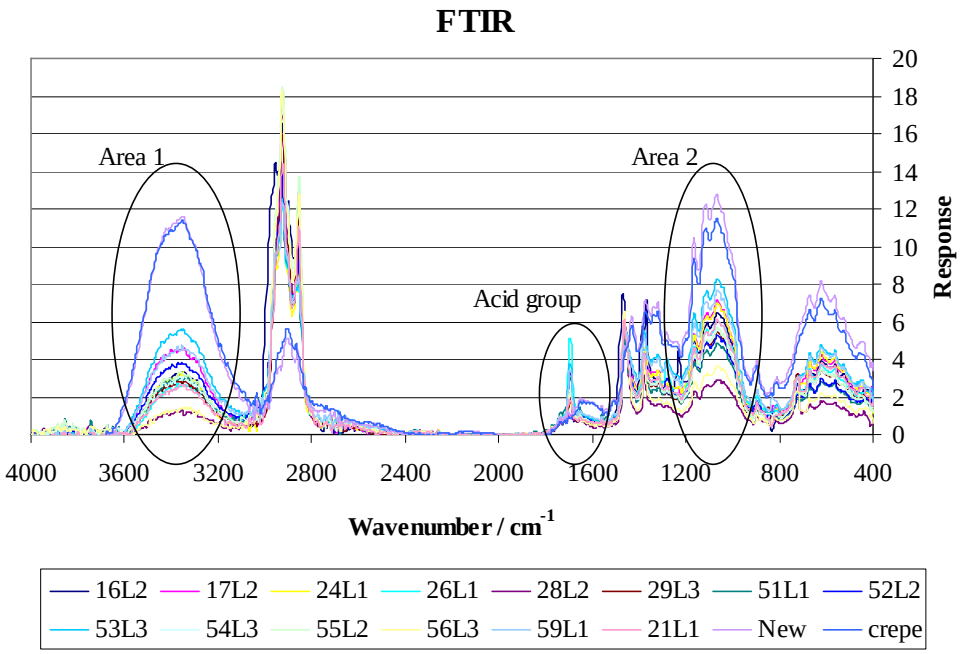

Figure 6.13 Measured FTIR-spectras on oil-paper insulation samples.

The area between the spectra and baseline in the acid group region between wavenumbers 1500 – 1800 cm^{-1} can be used for moisture content analysis [52]. The area will increase when the moisture content increases independent on of the water form. An increased acid group area also indicates that the pH-value of the paper is decreasing. The environment will be more acidic and hazardous when the pH-value decreases. The ratio of peak values 1 and 2 can be used for condition analysis. The peak value of area 1 is calculated from the band between wavenumbers 3200 and 3600 cm^{-1}, and the peak value of area 2 from the band between wavenumbers 900 and 1200 cm^{-1}. An increase in the ratio between the peak value of areas 1 and 2 corresponds to an increase in the moisture content. Table 6.4 shows area and peak ratio calculations results.

Figure 6.14 shows the correlation curve between cable age and the calculated acid group area. New and crepe paper samples are not included in the correlation calculations. The new and crepe paper are not impregnated and are most likely a different kind of paper to that used in cable insulation. The new paper samples had been stored in a normal environment, giving rise to a high moisture content in them. Cable age and acid group area shows quite a good positive linear correlation. The correlation curve follows equation $y = a + bx$, where a = 23,17 and b = 5,68. A good correlation between the cable age and acid group area indicates clearly that the degradation of the studied cables was mainly caused by natural degradation, which depends on age. This is expected result for cables which have been used in quite low loading conditions, normally less than 50% of their rating.

Table 6.4 Acid group area and peak ratio calculation results.

Cable ID	Age a	Area	Ratio peak1 / peak2
16L2	29	180,7	0,514
17L2	42	200,1	0,646
24L1	41	230,2	0,471
26L1	51	308,9	0,456
28L2	31	180,5	0,467
29L3	31	195,9	0,524
51L1	42	289,4	0,643
52L2	42	255,6	0,725
53L3	42	293,7	0,683
54L3	33	224,9	0,548
55L2	33	239,5	0,586
56L3	33	209,4	0,395
59L1	42	296,3	0,618
21L1	34	214,9	0,436
New	1	362,9	0,910
Crepe	1	323,9	0,995

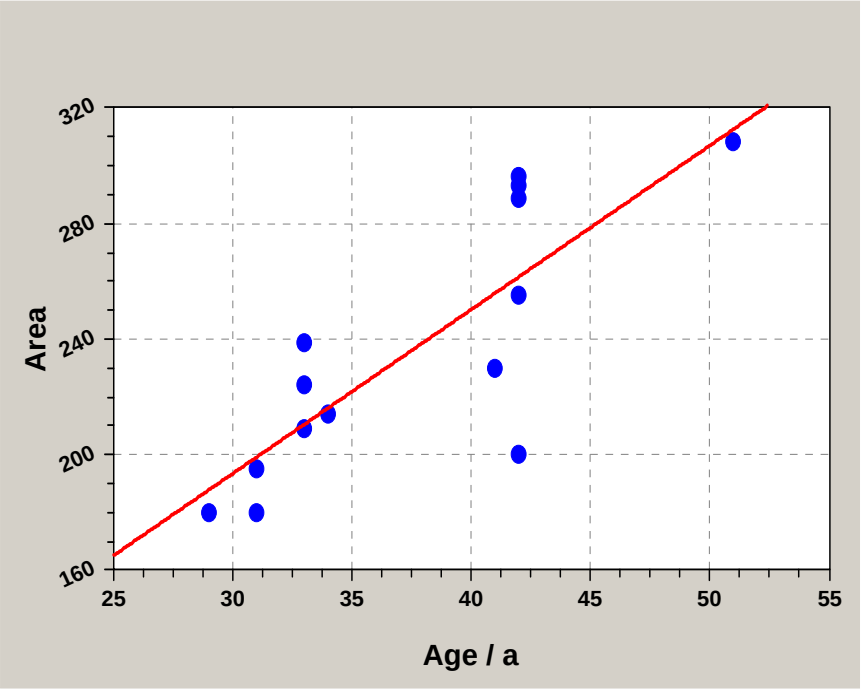

Figure 6.14 Correlation curve between cable age and acid group area.

Figure 6.15 shows the correlation curve between the acid group areas and the measured moisture content of the paper samples. Figure 6.15 shows a quite good exponential correlation which follows the equation $y = a \cdot e^{bx}$, with constants a = 0,0053 and b = 0,0197.

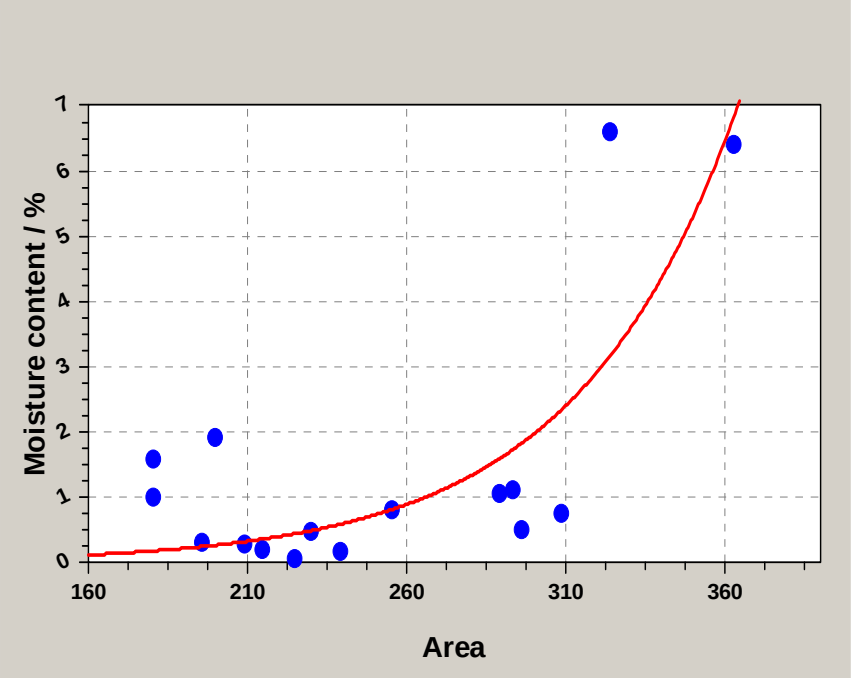

Figure 6.15 Correlation curve between acid group area and moisture content of insulation paper samples.

FTIR analysis can detect even a small amount of degradation in cable insulation, which is not detectable from a moisture content analysis or DP-value analysis. Some degradation processes will consume water and lower the moisture content. For example, the formation of acetic acid, typical for some paper qualities, will consume moisture. Formations of acetic acid will decrease pH-value and will also affect the acid group, as shown in Figure 6.13. A change in the acid group area can be detected using FTIR analysis. It is quite evident that there is a correlation between insulation paper moisture content and acid group area. This allows the possibility to use FTIR analysis to estimate the moisture content of insulation.

6.7 Artificial ageing tests

Two projects on studying chemically modified insulation papers were carried out during the years 1964 and 1966 [53 and 54]. The aim of these works was to compare the behaviour of normal insulation paper and thermally upgraded insulation papers. Some of the results from these projects are shown and analysed here. Also, some findings from references [57] and [59] are shown.

Different kinds of insulation paper were tested to determine their thermal behaviour. Accelerated lifetime testing was carried out on normal paper as well as chemically treated paper samples. Accelerated lifetime tests were carried out at temperatures of 150 °C and 170 °C. 150 mm wide paper samples were wrapped to form capacitors using thin aluminium foil. The weight of the insulation paper was around 20 g. The insulation paper samples were vacuum dried for 24 hours at a temperature of 110 °C. After drying, the paper samples were placed inside steel test pipes which were filled with oil. The test pipes were sealed tightly.

The status of the paper samples was checked regularly. The check points for 150 °C ageing were 0, 200, 700 and 1500 hours, and for 170 °C ageing 0, 43, 96 and 237 hours. Several parameters were determined for two samples taken at every check point. Parameters like the DP-value, acid content and bursting strain were determined. Figure 6.16 shows the degrees of relative DP-value of normal insulation paper and cyanoethylized insulation paper at different ageing temperatures. The nitrogen content of the cyanoethylized insulation paper was 3 %.

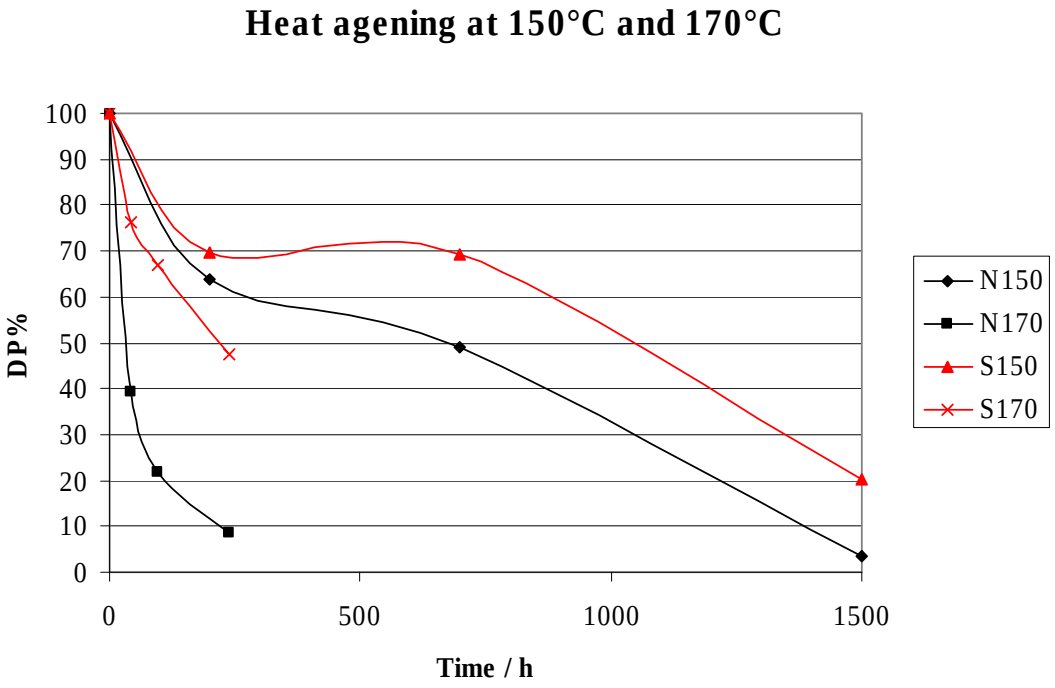

Figure 6.16 Degrees of relative DP-value of normal insulation paper (N150 and N170) and cyanoethylized insulation paper (S150 and S170) at temperatures 150 °C and 170 °C.

It can be seen that the overall performance of the cyanoethylized insulation paper was better throughout the tests; the absolute value of the DP was higher than the DP-value of normal insulation paper. The speed of ageing can be seen clearly when the inverse of the DP-value is plotted against ageing time. The slope of the line is the ageing rate [57]. Figure 6.17 shows ageing speed plots. It can be clearly seen that temperature has only a small effect on the ageing speed of cyanoethylized insulation paper. The ageing speed of normal insulation paper at a temperature of 170 °C is quite rapid and quite steady over the ageing time. The ageing rate of normal paper at a temperature of 150 °C is much slower at the beginning of the ageing time than at a temperature of 170 °C. After a certain point, the ageing rate speeds up dramatically. The reason for the increase in ageing rate may be the increased moisture and acid compound content.

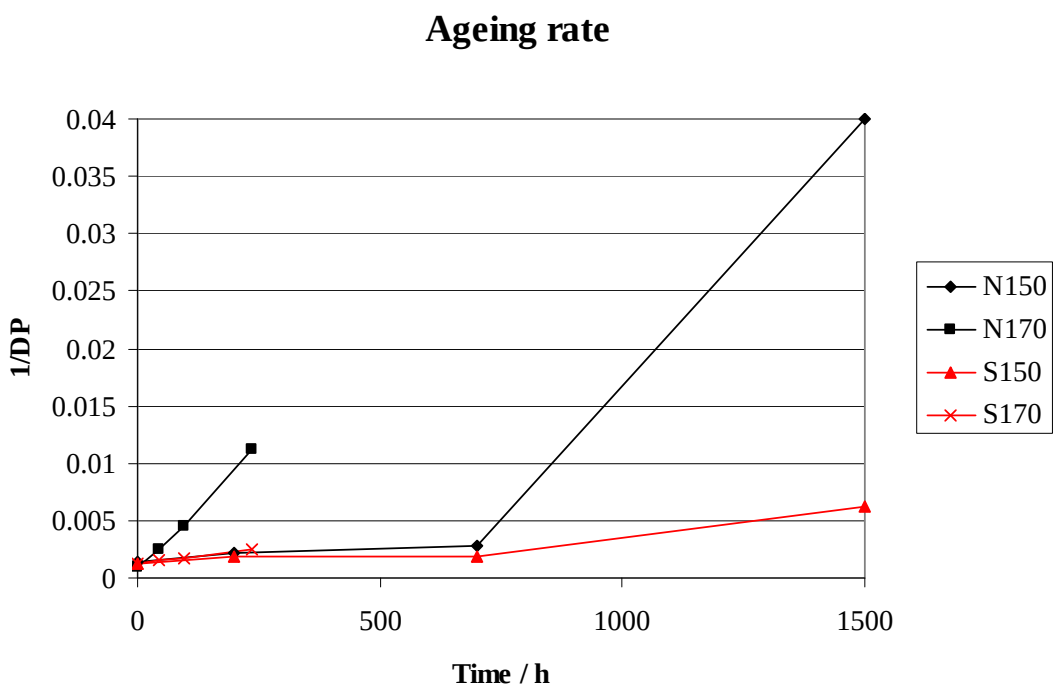

Figure 6.17 Ageing rate plots of normal and cyanoethylized insulation papers at two different temperatures.

Lifetime testing results at high temperatures can be converted to lifetime expectation at normal operating temperatures using the Arrhenius expression

$$L = A \cdot e^{\frac{\phi}{kT}} \tag{6.3}$$

where L is the time to reach the end of life (h), A is a constant, ϕ is the activation energy (eV), k is Boltzman's constant ($0{,}8617 \cdot 10^{-4}$) and T is the absolute temperature (K).

The Arrhenius equation can be expressed in the following special form [56]

$$\ln\left(\frac{t_0}{t_a}\right) = \frac{\phi}{k}\left(\frac{1}{T_0} - \frac{1}{T_a}\right) \tag{6.4}$$

which can be explained as follows: heating the test sample at temperature T_a for time t_a will produce the same amount of reaction as heating the sample at temperature T_o for time t_o. In cases where the ageing tests are carried out at only two different temperatures, equation 6.4 can be used to evaluate the activation energy.

If the activation energy is known, the service lifetime t_s at temperature T_s can be calculated from equation 6.5.

$$t_s = t_a \cdot e^{\left(\frac{1}{T_s} - \frac{1}{T_a}\right)\frac{\phi}{k}} \tag{6.5}$$

The end of life for paper insulation is reached when the DP-value goes below 200. This is the value when the paper has lost its mechanical strength. Another quite often used end of life criterion is the 50 % limit of tensile strength of insulation paper. Figure 6.18 shows the Arrhenius life plots for three different kinds of insulation paper, normal (N), thermally upgraded (T) and cyanoethylized (S) insulation paper. The end of life criterion is the DP-value falling below 200.

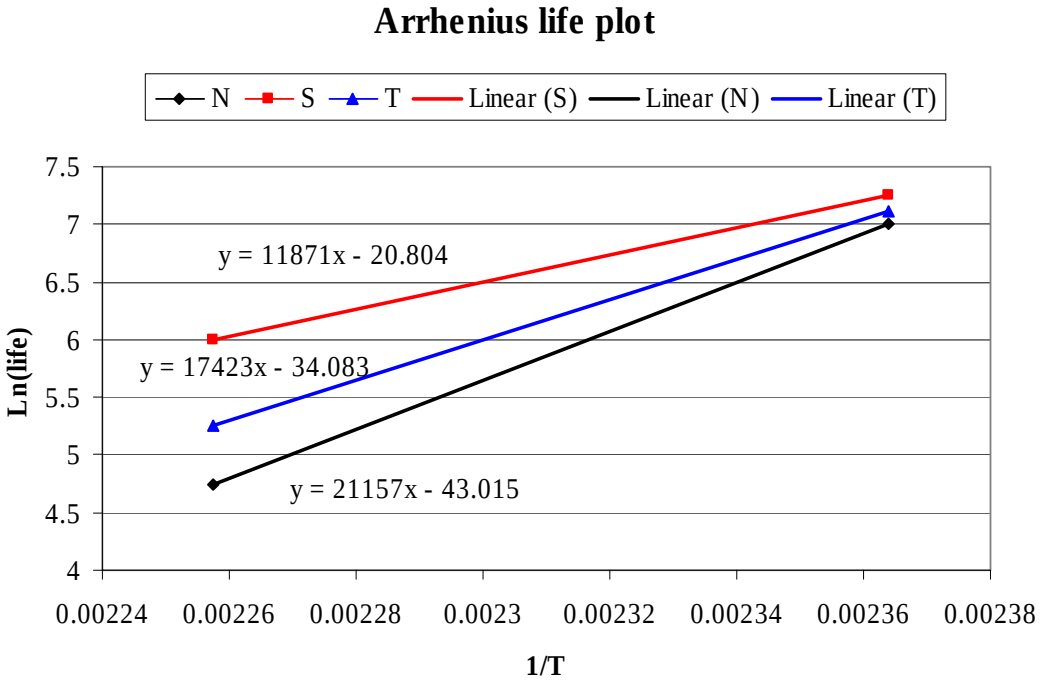

Figure 6.18 Arrhenius life plot for normal (N), thermally upgraded (T) and cyanoethylized (S) insulation papers.

As can be seen from Figure 6.18, results based on only two measuring points (temperatures) are somewhat confusing. Extrapolation of the life curves down to lower operation temperatures would indicate that the expected lifetime of normal paper would be longest. Expected lifetimes of dry paper samples at a temperature of 70 °C based on the life plot or equations 6.4 and 6.5 gives a result of more than 110 years for all paper types. Based on this finding, it is quite obvious that the degradation of insulating paper in cables operating at moderate temperatures and in dry conditions is a slow process.

The previously shown results are from ageing tests on dry paper samples. The paper samples were dried before the test so that the initial moisture content was low. The paper insulation of cables is also dried out before jacketing during the manufacturing process. Initial moisture content is low if the correct manufacturing process is adhered to. During normal service life, the moisture content of paper insulation can increase rapidly due to malfunctions in the protective layers of the cable constructions. External forces such as digging can cause scratches on the jacket, which may lead to moisture penetration into the insulation. Accessories may also have

some leakage problems causing an increase in moisture content. It is known that certain types of joints are prone to leakage problems, probably due to thermal movements during the service life.

An increased moisture content has a great effect on the degradation rate of insulation paper, as can be seen from Figure 6.19. Figure 6.19 shows ageing test results from dry and wet test samples tested at a temperature of 150 °C. Wet test samples, marked in Figure 6.19 with subscript w, were treated in a similar way to the dry ones, but before sealing the steel test pipes, deionised water was added so that the initial moisture content of the normal paper (Nw) was 2,1 %, thermally upgraded paper (Tw) 1,1 % and cyanoethylized paper (Sw) 1,4 %.

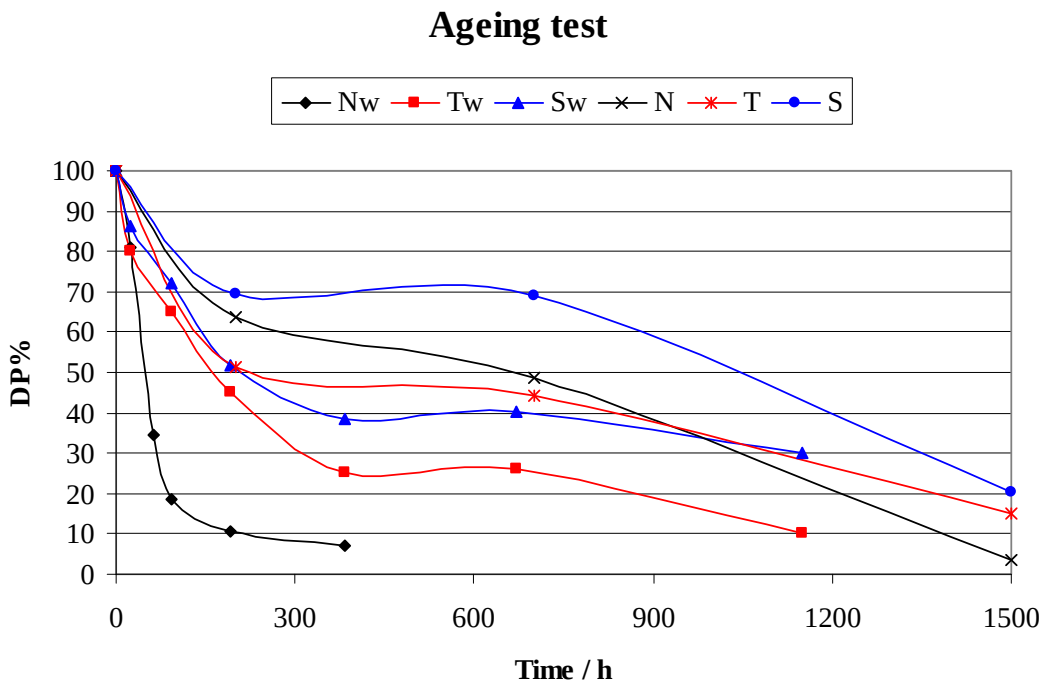

Figure 6.19 Ageing test results. Relative DP-values for dry and wet normal (N and Nw), thermally upgraded (T and Tw) and cyanoethylized (S and Sw) insulation paper at a temperature of 150 °C.

Figure 6.20 shows the ageing rates for wet paper samples tested at a temperature of 150 °C and dry paper samples tested at a temperature of 170 °C. The ageing rate of wet normal paper samples at a temperature of 150 °C is almost identical to the ageing rate of a dry sample of the same paper type at a 20 °C higher temperature. Similar behaviour can be seen with cyanoethylized paper samples. The effect of increased moisture in thermally upgraded paper is weaker. It is clearly shown that increased moisture content will affect the ageing rate of paper insulation. The oil-paper insulation of cables will degrade much quicker than expected if the moisture content of the insulation increases rapidly. An increase in moisture can only occur if there is an accessory fault or an external fault on the cable jacket.

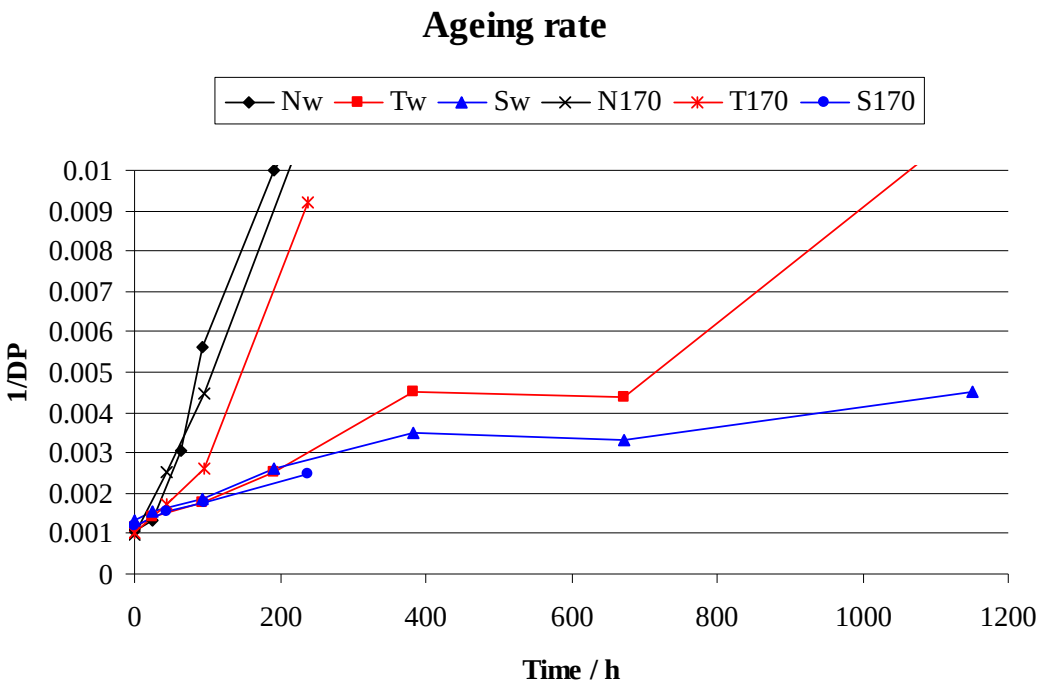

Figure 6.20 Ageing rate of wet test samples (Nw, Tw and Sw) at a temperature of 150 °C and dry paper samples (N170, T170 and S170) at a temperature of 170 °C.

An interesting point with regard to paper degradation is that moisture content does not necessarily increase when the DP-value decreases. This behaviour is shown in Figure 6.21. The moisture content of all paper qualities, shown in Figure 6.21, will decrease during the first part of the ageing test, as some degradation mechanisms and by-products will consume moisture at the beginning of the ageing. The formation of acids such as acetic acid will consume moisture. The breaking of cellulose polymer from its middle part will also bond water molecules. Longer ageing times, however, will lead to an increase in moisture content. The increased breaking of cellulose polymers will occur in the end regions of the polymers releasing water and glucose molecules. Still later, the breaking of glucose molecule rings will also release water molecules. The degradation process is self-catalytic; increased moisture content will increase the degradation rate, which will release more moisture to speed up the degradation.

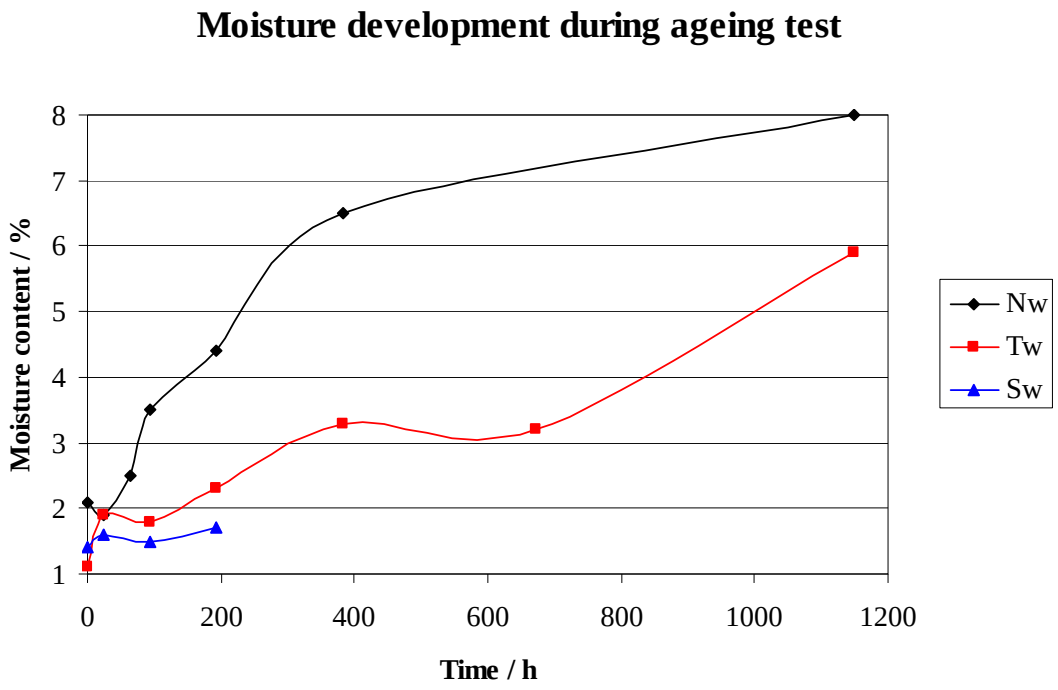

Figure 6.21 Development of moisture content during the ageing test of wet normal (Nw), thermally upgraded (Tw) and cyanoethylized (Sw) test samples at a temperature of 150 °C.

The relation between moisture content and DP-value is not a monotonic function, so in some regions a decreasing DP-value does not necessarily mean that the moisture content is increasing. However, there is an overall correlation between DP-value and moisture content. It is clear that in general, a decreasing DP-value correlates with increased moisture content of the insulating paper. Based on the experimental ageing tests, there is a clear exponential correlation between the moisture content of insulation paper and DP-degree. Correlation curves are shown in Figures 6.22 and 6.23. The correlation equation has the form $y = a \cdot e^{bx}$, with constants a = 6114,7 and b = -1,02 for normal paper and a = 1723,1 b = -0,59 for thermally upgraded paper. The correlation coefficient for the normal paper was 0,94 and for the thermally upgraded paper 0,97, both showing good correlation.

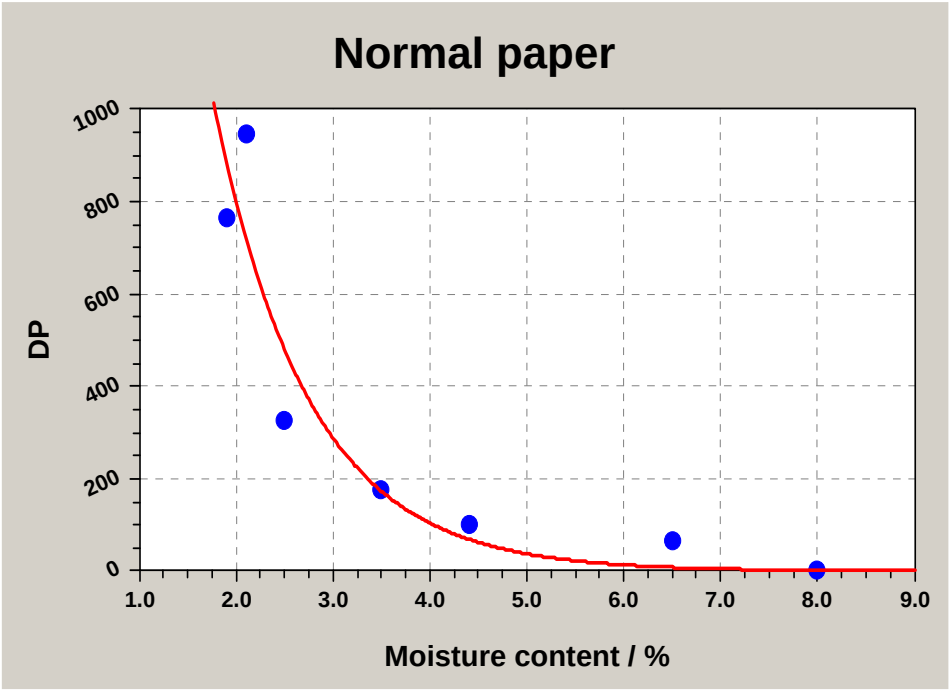

Figure 6.22 Correlation curve between moisture content and DP-value for normal insulation paper.

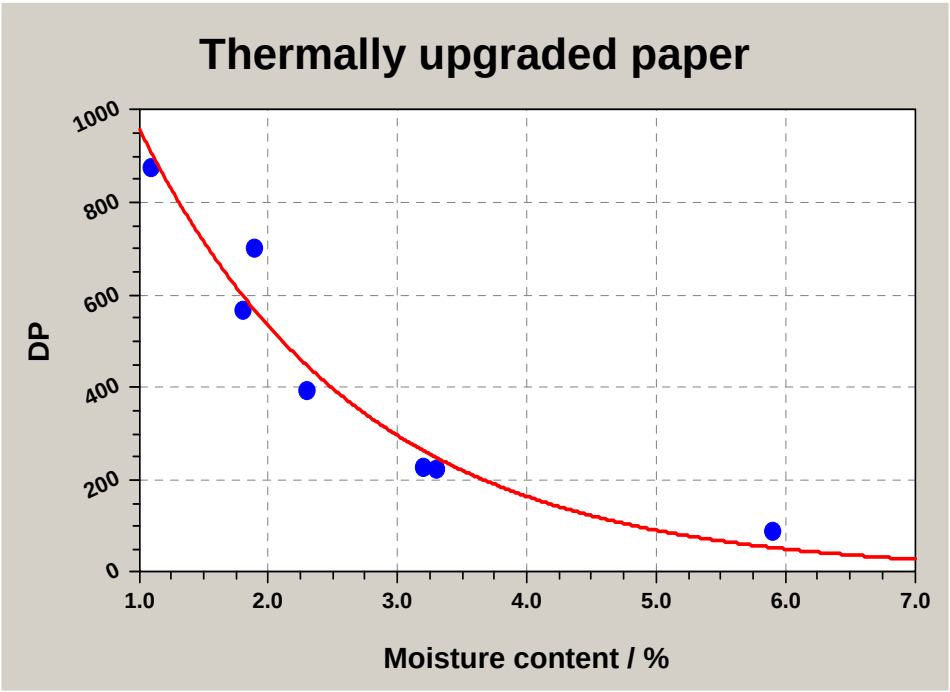

Figure 6.23 Correlation curves between moisture content and DP-value for thermally upgraded insulation paper.

The Arrhenius equation can be mathematically expressed in the following way, as a life expectancy (years) fraction depending on temperature and environmental aspects [59].

$$Expected\ Life = \frac{\frac{1}{DP_t} - \frac{1}{DP_0}}{A \cdot 24 \cdot 365} \cdot e^{\frac{\phi}{RT}} \qquad (6.6)$$

Where DP_t is the DP-value at the end of life and DP_0 is the DP-value at the beginning. A is a constant depending on the chemical environment, ϕ is the activation energy, R is the molar gas constant (8,314 J/mole/K) and T is the absolute temperature.

The expected lifetime plot for normal paper, showing the effect of moisture content and temperature, as shown in Figure 6.24, can be plotted using equation 6.6. The plot shown in Figure 6.24 is based on the following assumptions: the DP-value at the beginning of the insulation life is 1300 and at the end of life 200, the activation energy is 111 kJ/mole and the environment constant A values are as reported in reference [57].

As can be seen from Figure 6.24, the temperature and moisture have a significant effect on the expected lifetime of paper insulation. A 4 % moisture content will shorten the life of insulation by about twenty times compared to dry insulation. The effect of temperature can be even higher. At moderate temperatures, the expected lifetime is still long even though the moisture content is high. Increased temperature will shorten the lifetime dramatically. This is in good correlation with the findings of the previously shown artificial test results.

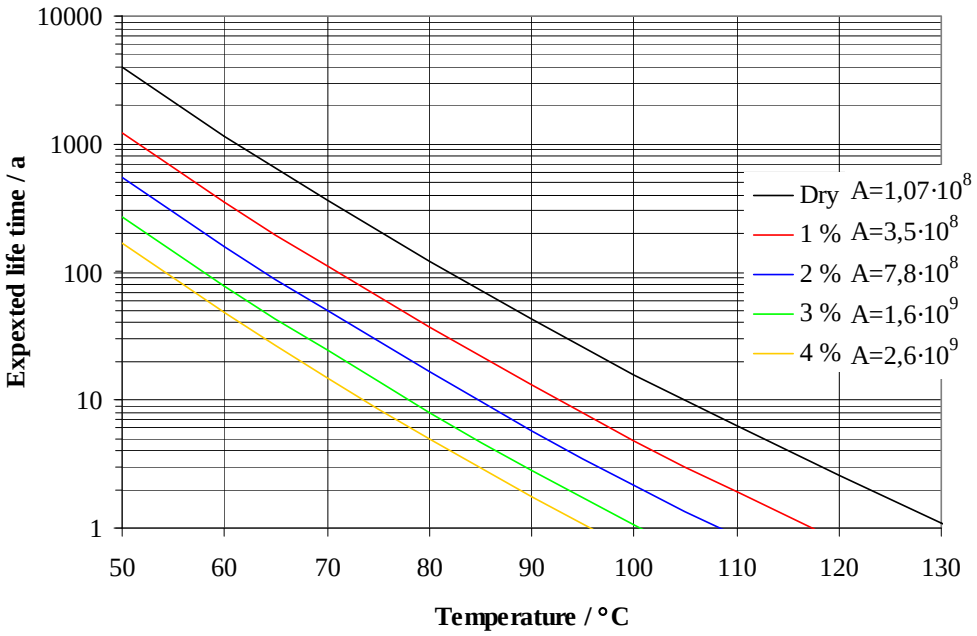

Figure 6.24 Expected lifetime of normal paper insulation at different moisture contents and temperatures.

6.8 On-site test results on oil-paper insulated cables

During the years between 2002 and 2007, on-site measurements of medium voltage cables were performed at several different locations. The on-site measurements comprised of dielectric

response measurements in the time domain together with partial discharge measurements. Figures 6.25 and 6.26 show the calculated PI-index and CF-index values of the measured cables.

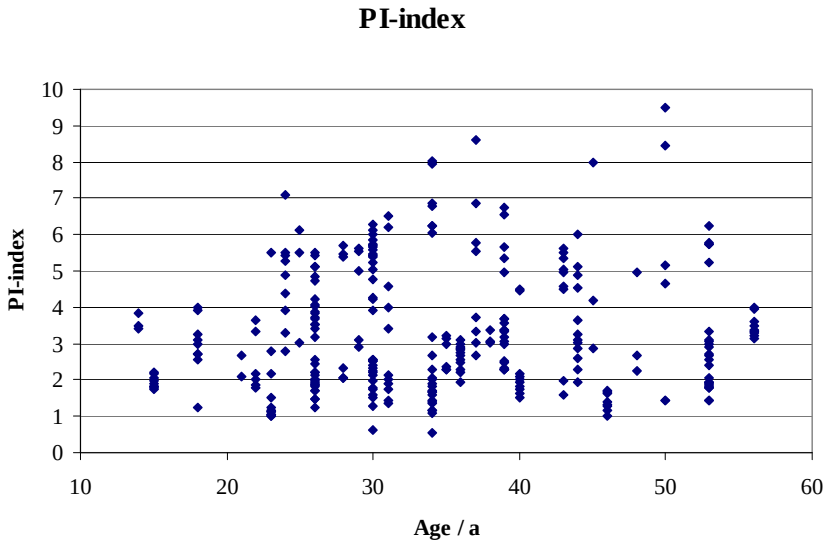

Figure 6.25 PI-index values of oil-paper insulated cables measured on-site.

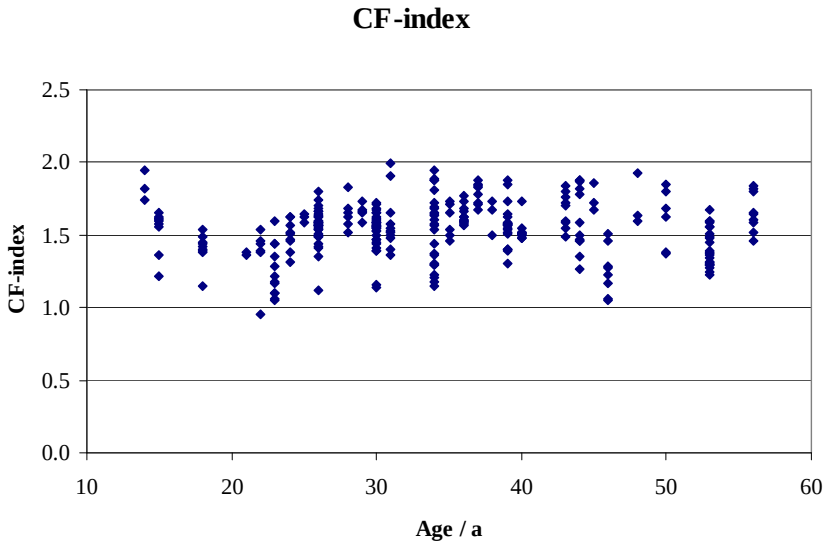

Figure 6.26 CF-index values of oilpaper insulated cables measured on-site between 2002 and 2007.

The total number of cables included in the figures was 100, giving a total of 300 measurements results on single phases. The age of the measured cables varied from 14 to 56 years. The PI-index and CF-index values do not correlate to the cable age, as can be seen from Figures 6.25 and 6.26. Variation in the index values for cables of the same age is quite large. This finding supports the conclusion that a cable's condition is not directly linked to its age. Based on these measurement results, a 56 year old cable can be as good as a 14 year old cable.

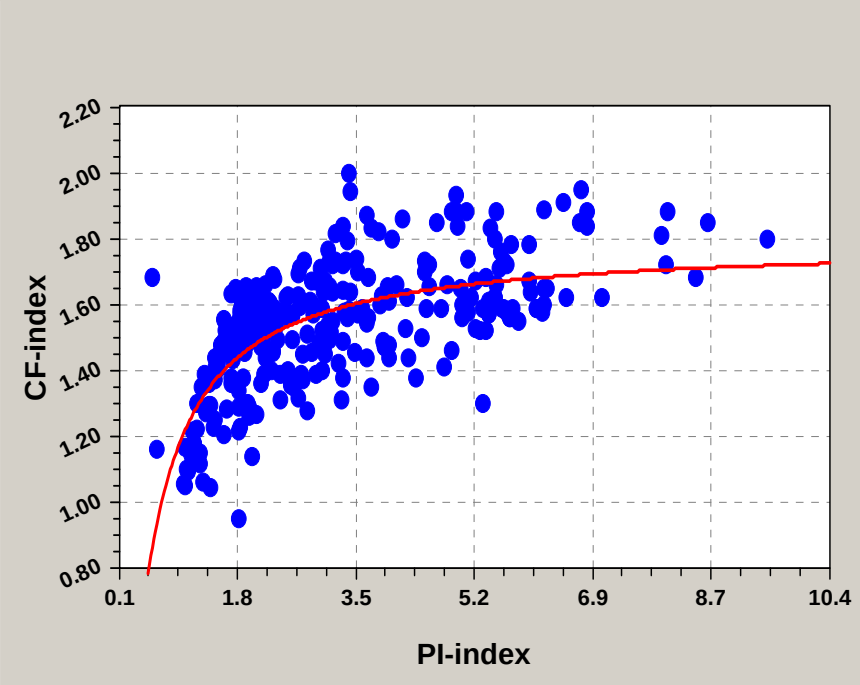

Figure 6.27 The correlation plot between the PI-index and CF-index values of on-site measured oil-paper insulated cables.

Figure 6.27 shows the correlation plot between the PI-index and CF-index values. The correlation curve plotted in Figure 6.27 follows the equation $y=ab^{1/x}$, with constants a = 1,79 and b = 0,68. The result is quite similar to that shown in section 6.2. Both indices can be used to estimate insulation condition.

6.9 Combined results and discussion on oil-paper insulation

Moisture content and the degree of polymerisation DP are the most commonly used variables to describe the condition of oil-paper insulation. Moisture is the most powerful degrading agent in paper insulation. Increased moisture content will increase dielectric losses and cause extra heating of the insulation. Moisture will also speed up the degradation processes. The degree of polymerisation determines the mechanical properties of paper. A lower DP-value will finally lead to complete loss of the mechanical strength of the insulating paper.

An increased moisture content will affect the electrical performance of oil-paper insulation. Changes in moisture content can be measured without destroying a cable's construction. A change in DP-value does not directly affect the electrical performance of insulation, but determination of the DP-value or moisture content requires a paper sample from the insulation. The natural time for taking a paper sample would be during the repair following a cable failure.

Measurement of the dielectric response in the time and frequency domains was performed on 25 three-phase cables; the total number of individual phases measured was therefore 75. The results showed that there is no correlation between cable type or cable age and dielectric response. The results also showed that the direct correlation between the time and frequency domain results is weak. A logarithmic correlation between loss factor minimum and estimated

conductivity was found. Both dielectric response measurement methods can be used to obtain a similar estimation of cable condition.

The correlation between dielectric response measurement results and moisture content analysis results was weak. A moisture content analysis measures only the moisture in the paper part of the insulation. During a dielectric response measurement, polarisation and other important phenomena are activated in the paper as well the oil component of a cable's insulation. In this study, the chemical analyses were only applied to paper samples but not the impregnating oil. An increase in the conductivity of oil will also affect the dielectric response, giving rise to worse conditions than a paper analysis alone shows.

Most of the cable samples were quite dry. The moisture content of all field aged cable samples was lower than 2 %, while new paper samples showed moisture contents of more than 6 %. The new paper samples had been stored freely in environment conditions. The new paper samples absorb a high amount of moisture from the air. During the manufacturing process insulation paper has to be dried out. The low moisture content supports the finding that the DP-values of the paper samples were high, even higher than the new reference sample. A high DP-value means that the mechanical properties of the paper insulation have changed only a little. The mechanical properties of the insulation papers were not a limiting factor on the cable insulation performance at the time the samples were taken. The increase of moisture content together with high temperatures can speed up degradation and lowering of DP-value dramatically.

Taking into account the DP-value and results from the ageing tests, it could be stated that the mechanical lifetime of the paper insulation at moderate temperatures is still long, several decades. External mechanical stress on the oil-paper insulation should be avoided, even if the expected mechanical lifetime is long. Although the used insulation paper strips themselves could handle similar mechanical forces to those a new paper sample could tolerate, the mechanical strength of the whole insulation structure may be decreased. In new impregnated cable insulation, the paper strips wound on top of each other can move during the application of mechanical forces. With old insulation, the paper strips may become "glued" together, preventing movement. In some cases, the insulating oil can form a wax, which will affect the electrical performance of the insulation structure. For example, the bending of an old cable might cause ruptures in the paper layers. In the worst case, these ruptures may go through the entire insulation thickness, causing a radial breakdown channel.

Calculation of the acid group area from the FTIR spectrum showed a clear correlation between area and cable age. Further, it was found that there is a correlation between acid group area and the moisture content of the cable insulation samples. Based on this finding, FTIR analysis can be used to estimate the moisture content of paper insulation. As is the case for XLPE cables, the most convenient time to take paper samples for FTIR-analysis is when cables are being repaired following a failure. A paper sample can be easily taken during the insulation stripping. The paper sample should be stored in a glass bottle, which should be sealed airtight. The paper sample must be sent for analysis as soon as possible. After two weeks the sample is not useful anymore.

Baseline correction must be applied to FTIR-spectra before area calculation. The average value of wavenumbers 1900 – 2400 cm^{-1} should be subtracted from each wavenumber value for baseline correction. After baseline correction, the area between wavenumbers 1500 and 1800 cm^{-1} should be calculated.

Based on the experimental results, the moisture content of paper insulation and expected lifetime can be estimated according to Table 6.5. The moisture content is based on the correlation between acid group area and the measured moisture contents. The expected lifetime at different temperatures is based on experimental results from the artificial ageing test. Even insulation containing a high amount of water can survive a long time in operation if the temperature is relatively low. At higher temperatures, starting from 70 °C, high moisture content will reduce expected lifetime significantly. The operating temperature of the cable conductors should always be well below 90 °C.

Table 6.5 Estimation of the moisture content and expected lifetime at different temperatures for paper insulation based on acid group area.

Condition	Area	Moisture content %	Expected lifetime at 60 °C years	Expected lifetime at 70 °C years	Expected lifetime at 90 °C years
Very good	< 265	< 1	> 300	> 100	> 15
Good	265 – 300	1 – 2	150 – 300	50 – 100	6 – 15
Moderate	300 – 320	2 – 3	80 – 150	25 – 50	3 - 6
Poor	320 – 335	3 – 4	50 - 80	15 - 25	2 – 3
Bad	> 335	> 4	< 50	< 15	< 2

With regard to these results, it should be kept in mind that the relationship found between acid group area and moisture content is based on the measurement of rather dry samples. Analysis accuracy can be improved in the future by performing FTIR analysis and moisture content analysis in parallel on more samples. The cost of an FTIR analysis is less than a normal moisture content analysis. The cost of one FTIR analysis is around 200 – 350 euros, and the cost of one moisture content analysis is around 500 euros at the time of writing. FTIR analysis can also provide more information about the chemical status of the insulation. Even small changes can be detected when applying FTIR analysis to an insulation sample.

7 Conclusions and future work

7.1 Conclusions

Two major insulation systems used in Finnish medium voltage networks were chosen for this study. Most of the medium voltage cables used in Finland are either oil-paper insulated or XLPE insulated. Only a small minority in some special places use other insulation structures. Insulation structures and major degradation processes were presented. A short review of the analysis methods used in the experimental part of the work was also presented.

A large measurement and analysis programme on field aged XLPE insulated and oil-paper insulated cables was carried out and formed the practical foundation for this thesis. Different kinds of non-destructive electrical diagnostics measurements, such as dielectric response measurements, were performed on the same cable samples that were subjected to destructive testing.

The XLPE insulated cables tested in this study were taken from a good environment. The cables had been installed on cable racks in a tunnel. Based on the results of this study, the following conclusions on XLPE-insulated medium voltage cables can be made:

- The age of a cable does not show any correlation with measured diagnostics variables. Cable age does not correlate with the actual cable condition.
- The FTIR analysis result, carbonyl index A, shows a correlation to the voltage withstand level of cable. The results indicate that FTIR analysis can be used to evaluate cable condition.
- Cables, even without a radial water barrier, when used in a friendly environment are in good condition after 30 years in service.

Oil-paper insulated cables of different ages and different types were collected from several different utility companies. Various kinds of diagnostic measurements were carried out on these samples. Diagnostics methods applied on this study were focusing on properties of the paper insulation. Effect of the oil degradation was not studied. Based on the results from this study, the following conclusions can be made:

- The age of a cable does not show a correlation with any measured diagnostics variable. Cable age does not correlate with the actual cable condition.
- The insulation paper of all analysed samples was dry, moisture content was less than 2 %.
- The mechanical strength of paper insulation is not the limiting factor of insulation performance. The DP-value of all samples was higher than 1000.
- The FTIR analysis result, acid group, has a correlation with the moisture content of insulation. FTIR analysis can be used to estimate cable insulation condition.
- Increased moisture content and high temperature have a dramatic effect on the degradation rate of paper insulation.

Based on the findings, it can be said that FTIR analysis can be used to evaluate the condition of medium voltage cables. FTIR analysis can be used on XLPE as well as on oil-paper cables.

FTIR analysis has some benefits compared to other methods. FTIR analysis is faster, cheaper, and it can be done in several different places. Collecting samples during the repair period following a cable failure would not require lot of extra work. The FTIR spectrum analysis methods shown in this publication do not require any deep knowledge of method or the chemistry of insulation. Deeper knowledge of the chemical reactions involved in insulation degradation together with FTIR analysis can give an even more precise evaluation of insulation condition. However, such a deep chemical analysis of FTIR spectra has not been performed in this thesis.

7.2 Future work

Future work and development is required, although FTIR analysis seems to work quite well on both insulation structures that were tested in this study. In this thesis, several methods were tested and analysed. In future work, the availability of some of these and other methods should be improved.

The XLPE insulated cables in this study did not have a radial water barrier and were used in friendly environmental conditions. A similar study, focusing on voltage withstand levels and FTIR spectra, should be carried out on cables installed in the ground and dry design cables with radial water barriers.

The effect of conductor temperature on the carbonyl content in XLPE insulated cables is not well known. This could be important information for urban network planning in the future, when power demand during the summer may increase. A change in carbonyl content might be one of the limiting factors for conductor temperatures in long run.

FTIR analysis on oil-paper insulated cables together with traditional moisture content analysis should be done to get a more precise calibration curve. A calibration curve would link FTIR-analysis results tightly to the moisture content of insulation. These analyses should be carried out on cables of different age and type. Cases where moisture content is likely to be high, e.g. due to termination leakage, should also be analysed.

All analysed oil-paper cables were rather dry and the DP-value was still high. The tested cables were all more or less naturally aged. Increased power demand during warm summer periods could lead to rapid degradation of oil-paper insulation. Knowledge about the degradation of insulating paper is based on artificial ageing tests carried out on new paper samples. The long term performance of used paper insulation could be estimated by performing an artificial ageing test series on insulation that has been used for more than thirty years. This type of test series, made at different temperatures, could give valuable information of the expected lifetime of old oil-paper insulation.

In this study degradation of paper insulation was studied. In the real oilpaper insulation degradation of insulating oil will also play a role. Effect of combined degradation on the performance of the hole insulation structure should be studied in the future.

Overall collecting and analysing of different types of cable insulation samples should be carried out on a regular basis to detect possible changes in the insulation structure. It could be that once changes and weakening of insulation starts, the process to the final breakdown might be quick. With regard to this point, the development of cable maintenance strategies will play an important role. Development and planning of operation models to avoid an otherwise inevitable increase in cable failure rates should be undertaken in the near future.

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Appendix: Author contribution on individual publications included as reference

In this dissertation, the author has been marked as the main or co-writer in eleven different references. Following list shows the author's contribution in these eleven individual publications included as references in this thesis. The references are listed in chronological order.

- P.Hyvönen. Dielektrisen vasteen mittausmenetelmien teoreettinen perusta. Basic theory for dielectric response measurements, written in Finnish. Helsinki University of Technology. High Voltage Institute. Report TKK-SJT-46. Espoo March 2001. 16 p.
  - The author was the sole author in this publication.
- P.Hyvönen, B.Oyegoke, M.Aro. Advanced diagnostics test and measurement methods for power cable systems on-site. Literature review with discussion. Report TKK SJT-49. Helsinki University of Technology, High voltage institute, Espoo, Finland, 2001.
  - The author has written the greater part of this literature review.
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  - The author has acted as co-writer, carrying out the empirical study presented in the report.
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  - The author has acted as co-writer, carrying out part of the writing and editing in co-operation with the other authors.
- P.Hyvönen, B.Oyegoke, M.Aro. Condition assessment of MV power cables based on practical measurements, NORD-IS 2003, June 11 – 13 2003, Tampere Finland 2003, 8 p.
  - The author has acted as the main writer and has carried out the practical measurements and data analysis shown in publication.
- P. Hyvönen. Keskijännitteisten maakaapelijärjestelmien osittaispurkausmittaukset käyttöpaikalla. On-site partial discharge measurements on medium voltage cable systems. Licentiate thesis written in Finnish, Helsinki University of Technology, Espoo Finland 2003. Report TKK-SJT-60, 96p.
  - This publication is the author's licenciate thesis.
- B.Oyegoke, P.Hyvönen, M.Aro. Experience with the application of time domain dielectric response method in condition assessment of distribution oil-paper. NORD-IS 2003. June 11 – 13 2003. Tampere Finland 2003. 8 p.
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  - The author has acted as the editor, collecting and writing down the main findings in several different reports produced during the KaDiat –project.
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  - The author has acted as co-writer carrying out the statistical analysis and evaluation of the needle test results.
- A.Harlin, M.G.Danikas, P.Hyvönen. Polyolefin insulation degradation in electrical field below critical inception voltages. Journal of electrical engineering. Vol. 56, No. 5-6. 2005. pp 135-140.
  - The author has acted as a co-writer, providing test samples and background information of used cables and editing the text focusing on the dielectric response measurement part.
- P. Hyvönen, A-S Jääskeläinen " Chemical changes and remaining voltage withstand of field aged XLPE-cables" NORD-IS 2007, June 11 – 13 2007, Kgs. Lyngby, Denmark 2007, 4 p
  - The author has acted as the main writer. The co-writer performed the FTIR-analyses and evaluated the FTIR-analysis results.

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